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**Structural Behaviour of Bending Active Structures.
The impact of load distribution, geometry, temperature and
wind loads on the structural performance.**

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ABSTRACT

With the advanced development and growth of engineering in the construction industry, the use of lightweight structures has received a significant amount of attention due to their advantages, such as lightness, portability and multi-purpose uses. Therefore, new ideas and methods in design and construction have gained popularity in the building sector. The development of the Bending Active Theory played a crucial role in this process and, therefore, this study includes detailed descriptions of its historical evolution and the mathematical and structural theories behind its use in the building sector. As the existing studies mainly focused on architectural aspects, this research aimed to provide a better understanding of the structural behaviour of bending active structures under both internal stresses created due to bending and external loadings and investigate the impact of environmental temperature and lateral force for design and construction using laboratory tests and numerical modelling. Geometry, length, and cross-section are among the essential factors in the structural behaviour of bending active structures that their effects were also studied in this research.

The findings indicated that as a high f/L ratio could increase the deformations and cause the instability of the structure, the f/L ratio of up to 0.7 was recommended for bending active structures. As well as the effect of cross-sections on stress distribution, the orientation and angle of the component to which bending was applied significantly affected the level of stress created. The magnitude of the load did not directly affect the displacement, while the load distribution had a direct effect on the displacement. With the centralization of the applied load, the maximum stress created moved further away from the crown. Moreover, temperature loading influenced the behaviour and resistance of the GFRP materials. Cyclical temperature changes made the material more brittle, and the range of elastic behaviour decreased. In addition, fluctuations in the structure under the wind flow with higher velocity were limited, and the models were exposed to the wind flow with more rigid performance. With raising the f/L ratio, a rotating area was formed in the windward side near the ground.

Finally, based on the findings, a new design was proposed to prove the developed knowledge in a full-scale model. Also, this design showed the intelligent side of bending active theory, which flat elements could achieve a 3D structural shape with the ability of reversing back to their original shape without any permanent deformations caused and external support required.

SYMBOLS

Symbols	Description
$^{\circ}\text{C}$	Celsius
b	Across-wind characteristic
C	Courant number
c	Damping
C_p	Pressure coefficients
C_s	Smagorinsky constant
C_{μ}	Empirical constant
E	Young Modulus
$\tilde{E}$	Total Bending Energy
f	Model's hight
F_e	Elementary force vector
H_g	Boundary layer thickness
$I(z)$	Turbulence intensity in the longitudinal direction
k	Von Karman constants
$k(x_0)$	Local Curvature
k_e	Elementary stiffness matrix
L_e/r	Slenderness ratio
n_s	Frequency of vortex shedding
p	Pressure
p_0	Base pressure
p_{∞}	Freestream static pressure
p_{mean}	Mean pressure
q_{ref}	Dynamic pressure
r	Radius of gyration
$r.m.s$	Root-mean-square pressure coefficient
RF_x	Horizontal Reaction Force
RF_y	Vertical Reaction Force
$\bar{S}_{ij}$	Component of the strain stress tensor

Symbols	Description
S_{max}	Maximum Principal Stress
S_{min}	Minimum Principal Stress
S_t	Strouhal Number
T_0	Averaging period
U	Velocity
$\bar{U}$	Mean wind speed
$U(z)$	Wind velocity in the specified height equal to z
u^*	The frictional velocity based on the structure location
u^*	Friction velocity
U_e	Elementary displacement vector
u_t	Eddy viscosity
$\bar{U}_z$	Turbulence intensity
V_∞	Freestream velocity
z_0	Terrain roughness length
Z_{ref}	Reference height
Δ	Filter width
ρ	Air density
ψ	Catenary profile's average roof pitch

ABBREVIATIONS

Abbreviations	Description
AR-glass	Alkali Resistant Glass
BFRP	Basalt Fiber Reinforced Polymer
CEL	Coupled Eulerian-Lagrangian
CERF	Civil Engineering Research Foundation
CFD	Computational fluid dynamics
CFRP	Carbon fibre reinforced polymer
CTE	Coefficient of thermal expansion
CWE	Computational wind engineering
E-glass	Electrical Glass
FEA	Finite Element Analysis
FSI	Fluid-structure interaction
GFRP	Glass Fibre Reinforced Polymer
MC716	Closed Laboratory sample with 716mm span
MO716	Open Laboratory sample with 716mm span
MT716	Closed Laboratory sample with 716mm span with 20mm thick closer side wall
PDF	Probability Density Functions
r.m.s	Root-mean-square
RP	Rigid Pressure model
S-glass	Structural Glass
SPH	Smooth particle hydrodynamics

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CHAPTER 1

INTRODUCTION

This chapter gives a summary of the primary purpose of this thesis. Here, the overall context of the work and the background of the research project are presented. The aim and objectives are described.

1. Introduction

1.1. Introduction

The civil and architectural engineering sector is a fast-growing industry. An increase in the interest of modern structures' development has resulted in a significant progress in design and construction of lightweight and temporary structures. New technologies and theories have been continuously utilised to improve the essential parameters of these structures. The critical parameters in the design of successful lightweight structures are appropriate materials, fast and simple construction methodologies, and the ability to disassemble, transfer, and reinstall the structure without the need of skilled technicians, complex technologies, and expensive equipment.

The introduction of the Active Bending Theory represented a crucial step forward in developing innovative lightweight structures. Active bending theory refers to a structural principle that subjects the structural components to initial stress and bending deformations which are reversible as active bending theory defined in elastic range (Brancart S. D., 2014). The use of bending active theory in the construction can meet the significant parameters in the design of lightweight structures. In this research, structural behaviour of the bending active structures is assessed by investigating the components' internal force created due to initial bending and external factors.

1.2. Research Problem

Despite the current literature on bending active structures being produced by prominent researchers, the literature fails to provide a comprehensive investigation supported by extensive testing campaigns designed to assess the reliability of the structural behaviour.

In general, lightweight structures have been in use for centuries across a wide range of building sectors including emergency, leisure, sport, military, and trade (Beccarelli, 2013). However, during the last decade, bending active structures were gaining new interest. The great potential of such structures lies in their proven ability to expand the

structural morphology of lightweight structures with relatively easy manufacturing requirements (Brancart S. D., 2016).

These positive aspects make the bending active structures appealing; however, without understanding the proposed structures' structural behaviour, it is difficult to determine with a degree of accuracy of their full potential. A better level of understanding of structural behaviour enables architects and engineers to assess accurately. This study contributes to a further understanding of the structural behaviour of bending active components (including various in geometries, sizes, cross sections, and modulus of elasticity), validating this technology in real environmental conditions, which include complex geometries and loading conditions, interaction with wind, temperature's effect, challenges associated with the manufacturing of one-to-one scale structure, and the development of new structural concepts.

1.3. Research Aim and Objectives

Most studies investigating active bending structures were solely conducted in the architectural aspect. This research aims to provide a better understanding of the structural behaviour of bending active structures under both internal stresses created due to bending and external loadings as well as investigate the impact of environmental temperature and lateral force for design and construction. The factors examined in this study are:

- i. The geometrical parameters, such as the length, cross-section, and initial and final geometry. These factors directly affect the distribution of the structure's internal forces, which is a fundamental consideration during design.
- ii. During the procedure of the initial bending, the deformations should always stay in the elastic range, therefore, selection of the material play an essential role.
- iii. Temperature has an important impact on structures as it can affect the material's properties and lead to the progressive alteration of the resistance and stiffness of the material.

- iv. Wind load due to the complex 3D geometry and the light weight combined with the internal forces created from active bending is a crucial factor to be investigated for a formed design of bending active structures.

The objectives, which are shown as follow, will be carried out to achieve the aims of this research:

- Laboratory tests will be conducted to investigate the bending under various geometries and f/L ratios. The numerical simulations will be carried out under same conditions in laboratory tests, and the simulation results will be verified by the laboratory outcomes.
- Laboratory tests will be conducted to investigate the external point loading on the bent samples. The outcomes will be used to verify numerical simulations.
- To investigate the impact of environmental temperature on the bending behaviour, samples will be temperature-loaded in various forms, such as targeted temperature change (temperature change from primary to secondary temperature) and cyclic temperature (temperature change under specified cycles). After cooling the samples, bending and loading tests will be carried out at the ambient temperature.
- To investigate the exact effect of temperature loading on the material properties of the samples, tensile testing will be conducted.
- Using the findings from conducted tests and verifications, a further investigation of the effect of various geometries, materials, and f/L ratios will be performed by numerical simulations.
- The wind tunnel testing will be carried out for open and closed models with various f/L ratios to investigate the impact of wind.
- Using the obtained findings, a bending active self-supporting lightweight structure will be designed.

1.4. Research Method

The investigation of the structural behaviour of active bending components under various factors including geometry, load, materials, temperature, and wind loading will be conducted, according to the most appropriate approach adopted by similar studies. The effect of external factors on the distribution of forces and internal stresses will be investigated through physical laboratory tests and numerical modelling. The research framework is shown in Figure 1-1 and will be described in Chapter 3.

At the first place, the bending and loading tests will be carried out in laboratory experiments. Then, models using laboratory specifications will be simulated by ABAQUS software and the simulation results will be verified with the experimental outcomes. Using the verified findings, other complex factors such as geometry, load, and materials will be assessed numerically.

The effect of temperature on the structure's strength and stiffness will be investigated by applying temperature loading on the samples. The effect of lateral force on open and closed bending active models will be studied using wind tunnel testing. Finally, using the obtained findings, a mock-up will be introduced to demonstrate the usability of bending active theory in design and construction.

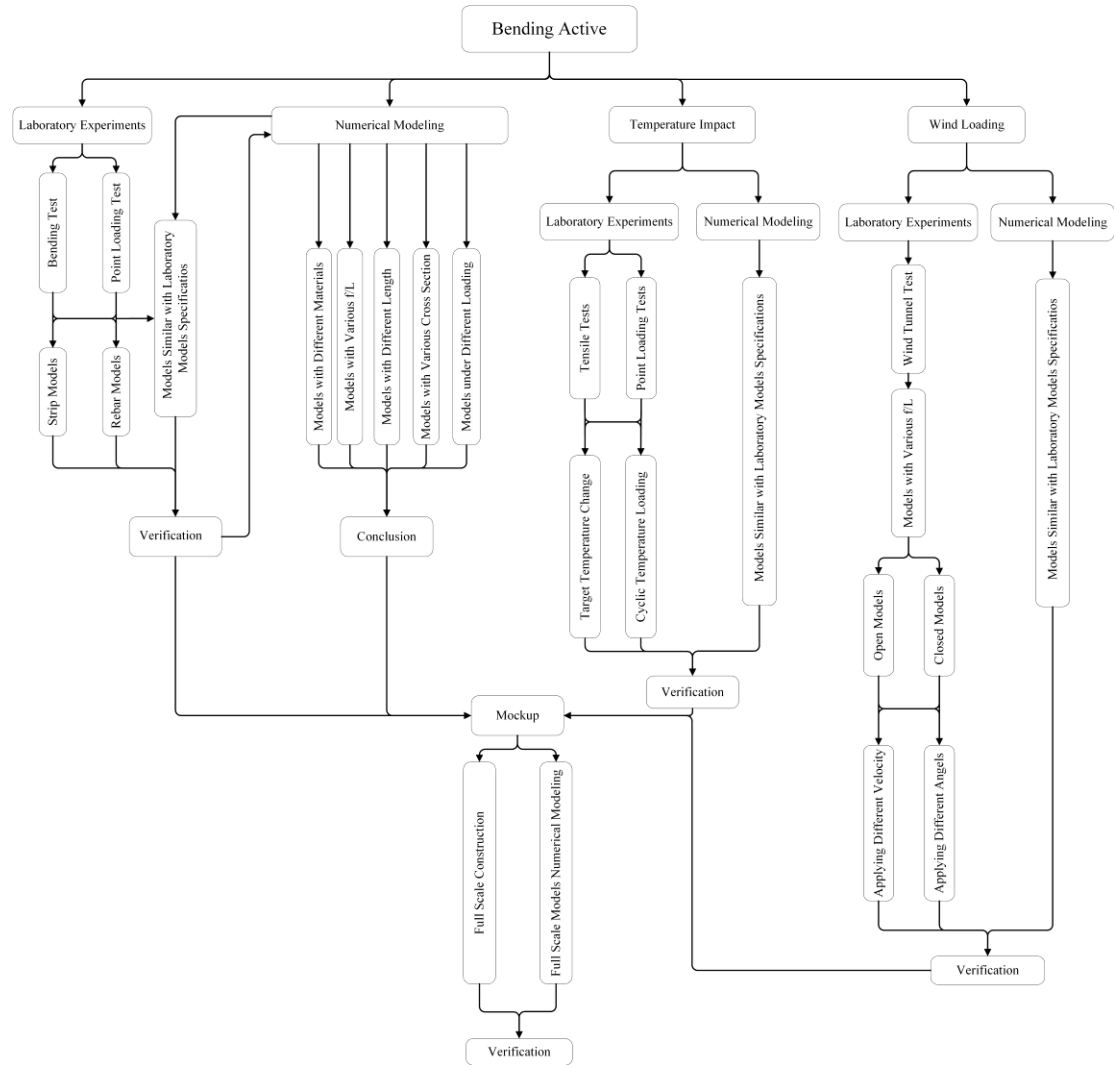


Figure 1-1: Research Flow chart

1.5. Research Structure

The present study is divided into six separated chapters investigating the structural behaviour of bending active structures.

Chapter one provides a summary of the primary purpose of the thesis. Here the overall context of work is presented, as well as the background of the research project and the aim and objectives in details.

Second chapter presents the basic structural concepts and reviews the research conducted in the bending active field, followed by the studies accomplished regarding

material characteristic used in active bending structures, environmental temperature impact, and wind loading effect on bending active structure or similar resources.

The third chapter describes methodology adopted for the experimental activities, including structural and mechanical tests as well as wind tunnel tests. This chapter includes the description of the laboratories and equipment used in the research, the procedures adopted to produce the samples and mock-up, as well as the testing procedures followed in the experiments.

In the fourth chapter, the results of experimental tests and numerical modelling related to the structural behaviour of active bending structures are discussed. The initial bending, loading tests, and temperature loading experimental outcomes are presented in the first part. In the second part, using numerical modelling, key factors for the behaviour of active bending structures, such as material properties, cross-sections, 3D geometries, and various lengths of the structural elements are investigated.

In Chapter 5, results for wind tunnel experiments related to the wind interaction on a scaled model are presented. Wind tunnel experiments are performed on models with different geometries in the form of open and closed models. In addition, other parameters, such as various wind velocities and flow angles are discussed. The final part of the chapter presents the comparison between the results obtained from the experimental and numerical models.

Using active bending theory, a self-supporting structure is designed and presented in Chapter 6. Firstly, the new design method is described and then a full-scale model is constructed. Finally, the structural behaviour and the manufacturing challenges are investigated through the numerical modelling and the full-scale model.

Conclusions with an overview of the outcomes obtained from the study, research limitation, and recommendations for the future research are presented in Chapter 7.

CHAPTER 2

STATE OF THE ART

This chapter presents the basic concepts of structural action and research conducted in the bending active field, followed by studies accomplished regarding material characteristic used in active bending structures, temperature loading impact and wind loading effect on bending active structure or similar resources.

2. State of the Art

2.1. Introduction

With the advancement of modern science and technology in engineering sciences, increasing attention is being given to the use of new methods and techniques in designing and constructing structures. Temporary and lightweight structures are one of the categories which have received considerable attention due to their features, such as the speed and cost of construction, as well as their wide application in various fields. The use of new technologies and theories in constructing structures is thus gaining increasing importance in the field. Bending active theory is one of the new theories in this area. Using the appropriate methods, the potential elastic energy of the elements can be utilised to construct and optimize structures (Montemurro, 2018).

This chapter first describes the basic concepts of Active Bending Theory. Then based on the categorization of these structures in the technical literature, the application of bending active structures as well as their production, use and history are discussed. In the following sections, the mechanical and structural behaviour of bending active structures is presented alongside an investigation into the industry's most suitable materials for cited structures. The following sections discuss the external and internal factors that alter the behaviour of bending active structures. Among these factors are structural and temperature loading, as well as the effect of wind load on the structure. Also, modelling and analysis of mentioned factors are discussed at the end of the chapter and numerical methods and appropriate software are described.

2.2. Structural Action

Structural action refers to the process of transmitting, receiving and transferring a load. There are many different approaches enforced in the categorization of structures. Describing 'families' of structural action in an abstract way (Engel, 1999) subdivides these families into not only 'types' but 'structure singles' as well. This logic shows how bending active structures can adapt and evolve into a plethora of different

categories of the structure by situating them upon the initial categories of structural action. It is also important to note that residual bending stresses are essential in the load transfer process inferred in bending active structures. The result of this is that bending active structures are uniquely different in comparison to the rest of the structural action families that (Engel, 1999) described.

Figure 2-1 depicts the way in which types of load-bearing structures differ, with structural action being the decider for categorisation and illustrates topological formations in each type of structural action. The figure portrays a fairly clear structural intervention in a typological manner and enables engineers and observers alike to understand just how much potential there is to be found with regards to the use of bending active structures (Lienhard, 2014).

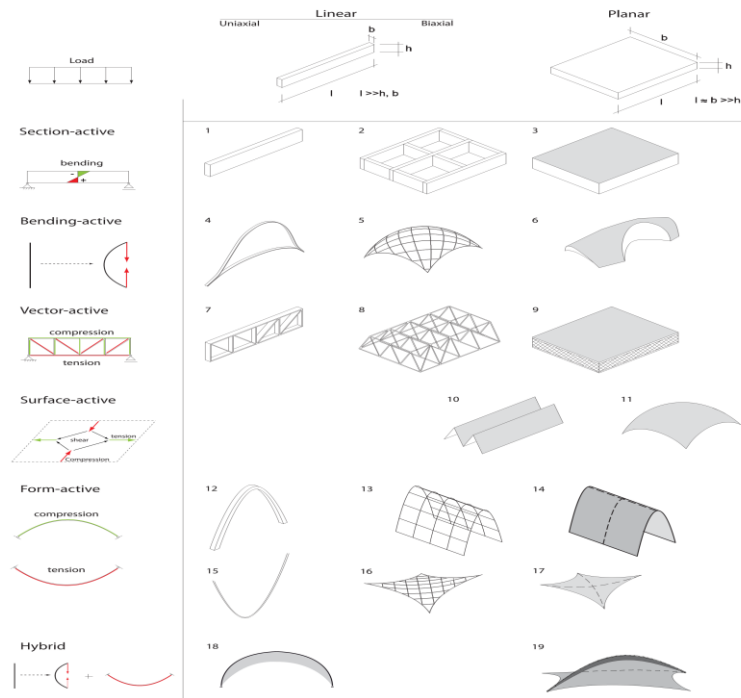


Figure 2-1: Differing types of load-bearing structures (Lienhard, 2014)

Surface-active structures refer to systems of flexible or rigid planes. Such structures are able to resist compression, shear or tension, in which the mobilization of sectional forces causes force redirection. These structures are formed with shells and plates and use a mixture of shear stress, compression stresses and surface tension in order to carry

external loads (the lack of bending components may be noted here). States of pure membrane stress can be activated in this kind of structure as the surface is aligned to coincide with the forces' flow. Typical examples of surface-active structures are folded plates, shells and plates which carry 'in-plane' loads.

Form-active structures refer to systems of non-rigid and flexible matter. In such structures, the redirection of forces is caused by both the particular form design and characteristic form stabilization. External loads carried by cables and membranes (pure tension) or arches (pure compression), bending moments or shear forces are non-existent in form-active structures. The flow of forces must be identified and matched with the load-bearing structures' geometry in order to achieve the construction of this kind of structure successfully. However, due to the variable factors of external loads, such as snow or wind, the geometry of this kind of structure must be adaptable to change and be able to deform. Form-active structures include membrane structures, catenary arches, shells and cable structures.

Hybrid structure is a structure that involves the purposeful combination of mechanisms of load transfers, where the main mechanisms simultaneously act within the structural system, even within a single structural element at times. Hybrid structures are typically a result of two dissimilar internal load parental systems being transformed and combined, resulting in a conjoined system. Suppose, in terms of structural capacity, and the two-parent systems are equal. In that case, they may be favoured in their paring as a hybrid system when extra rigidity is added via the deflection or the opposite system or/and when reciprocal stress compensation is enabled. Some classic examples of hybrid structures are the superposition of form-active and section-active structures or the superposition of surface-active and vector-active structures (Lienhard, 2014).

Active bending describes curved beam and surface structures that use the elastic deformation of initially straight or planar elements as a basis for their geometry (Lienhard et al, 2013). Generally, bending active is comprehended as an approach rather than a distinct category of structure. The common denominator of such structures is the formation process that elastically bends them, as opposed to geometrical

definition or the circumscribed load-bearing behaviour. Thus, active bending structures are widely comprehended as a subcategory of section-active structures. The load-bearing behaviour of bending active structures is similar to the surface- or form-active structures. This is a result of the capacity of such structures to develop real shell or arch properties in their final state of deformation. Moreover, bending active structures are characterized by the potential for both heterogeneity and structural integration. Thus, it may define as “structural systems that include curved beam or shell elements which base their geometry on the elastic deformation from an initially straight or planar configuration” (Vergauwen et al, 2017).

Large nodal displacements in structures that are statically indeterminate generate the prestress of active bending structures. The result of this is the deformation of individual building elements. In such structures, great importance is placed on the principle that the elastic limit of used materials is never reached by bending stress, which thus informs element stiffness. Therefore, investigations of such structures always use, which is a linear material law, with the large deformations evident in active bending structures influencing the use of geometrically non-linear calculations (Lienhard, 2014). The elastic bending of flexible components facilitates the simple realization of geometries of a curved nature from planar or straight elements, and ease of transportation and fabrication has been the main motivators behind active bending in ancient applications, such as the Mongolian Yurt (Brancart et al, 2016). Active bending is an interesting topic in architecture in a way that opposes the rigid outcomes of other techniques and facilitates outcomes and applications of a wide range of structural types and structures. The production and transportation of such structures are simplified, given that curvature is introduced in the assembly procedure alone. Despite the fact that the management of internal structural bending stresses in a structurally efficient and stable equilibrium can be a complex process, the outcome is often positive, showing marked improvements in the structure’s load-bearing behaviour. In bending active structures, the said self-restraint is induced via the creation of

topological incompatibilities, which is done by adding tensile elements (e.g., cables) or between the coupled binding elements.

For the current discussion on structural systems, Engel's terminology is used, which describes structural members as form-active due to their inseparable interdependence of force and form (Engel, 1999). Bending active structures are also characterized by their use of high strength materials and low bending stiffness, which guarantees the structure's sufficient load-bearing capacity. A growing interest in active bending is currently motivated by the recent evolutions in the techniques of digital simulation used in the structures, such as those used in the ICD/TKE Research Pavilion (Lienhard et al, 2011) and the M1 at La Tour de l'Architecte (Ahlquist et al, 2013). However, in many research projects, a number of questions remain about the structural and long-term behaviour of active bending structures such as fatigue due to loading, bending, temperature impact and the others.

Bending active structures do not describe a specific structural type but rather an approach. Based on the deliberately open definition of bending active, some types of bending active structures may be differentiated, although further research is required in these areas:

- Bending active elements
- Elastic Gridshells
- Bending Plate structures
- Textile Hybrids
- Elastic kinetic structures (Lienhard & Gengnagel, 2018)

2.3. Approaches and Types

In bending active structures, the common denominator is the process of formation, in which the elements are elastically bent, rather than a stringent geometrical definition or restricted behaviour of load-bearing. Consequently, a supplementary differentiation of structures that are bending active can be recommended, which uses approaches of design as a basis. Figure 2-2 is a graph that summarises three such approaches:

- In the ‘Behaviour Based Approach’, bending created initially in an intuitive sense, using trial and error procedure. The geometry of the system and its structural behaviour are studied empirically. In this case, physical testing is used to establish material limitations.
- In the ‘Geometry Based Approach’, the basis of the predefinition of the system’s geometry is the methods of experimental form-finding and the analytical geometry.
- In the ‘Integral Approach’, it is form-finding of the numerical kind that allows for elastic deformation analysis. This enables and allows full control of the geometry, which is based on material behaviour. In this case, limitations, as well as material characteristics, are integrated into the model of numerical analysis.

When reviewing the historical development, with the behaviour based approach as a starting point, it can be documented that it is this approach that enables the highest number of comprehended projects and is still a utilised and highly recognised method of construction. It was not until the 20th century that the analytical geometry-based approach was derived due to the active research of lightweight structures, which took place in the middle of the last century. In this approach, the creation of double-curved shell structures which possess geometry based on various differing experimental and analytical form-finding approaches (rather than the bending shape) is enabled through the use of elastic deformation. This method is highly economical. It is possible to combine these two methods with the use of the prevailing simulation methods available today. This is done through the simulation of bending deformations on a large scale of either the shape adaptations or the erection; therefore allows the full potential of active bending to be realised.

The presented examples in Figure 2-2 can be seen as being in historical order through the vertical axis, which also segments the approaches of design in accordance with the tools of analysis which are available, spanning from empirical, to analytical, before finally covering the modern numerical analysis. The interest mentioned earlier

on the lightweight and alternative construction principles from the 1950s is depicted in the centre of the graph in Figure 2-2, where an accumulation of the Geometric Approach projects is visualised (Lienhard, 2014).

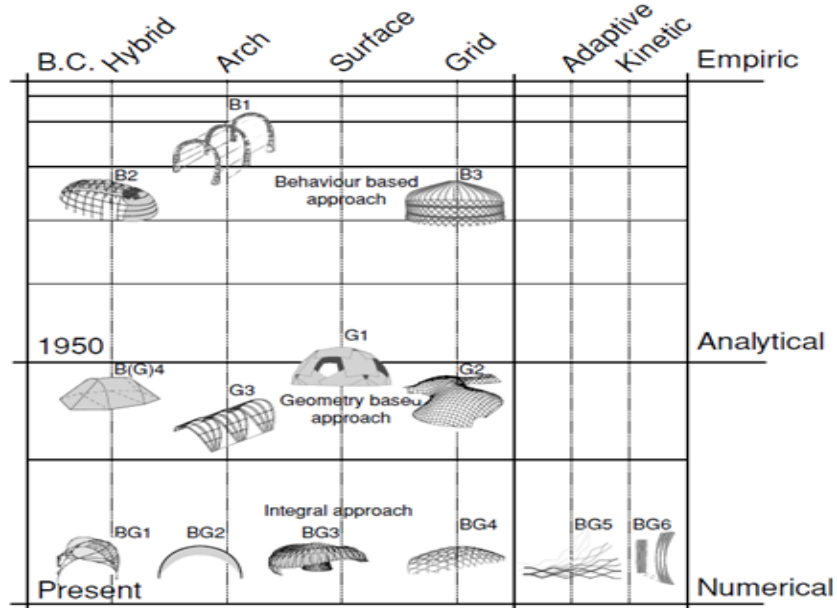


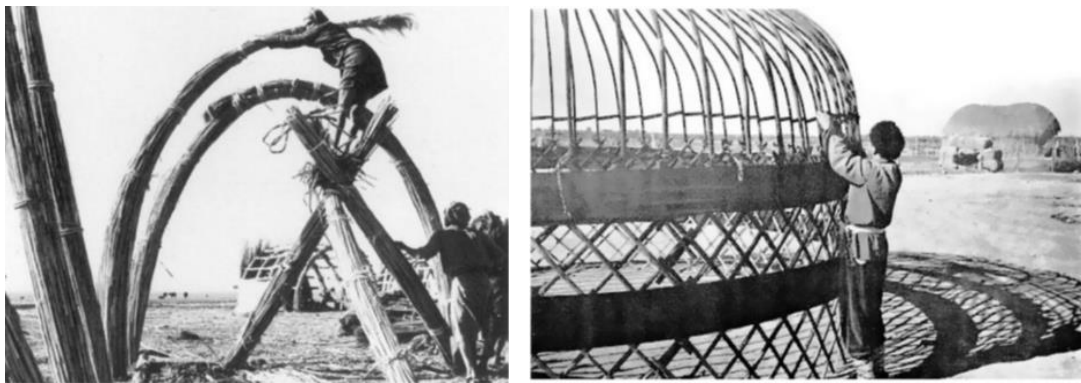
Figure 2-2: Development of bending active structures (Lienhard, 2014)

In the horizontal axis, a categorisation that is loosely formulated is depicted for the sorting of various terminologies of bending active structures into specific and recognised structural types. Most of the examples of recent days are placed purposefully indirectly to the exact axis, as in this case, the exploration between fresh ‘in-between fields’ and hybrid adaptations of the established structural types is just beginning. In the next sections, the essence of these mentioned approaches will be discussed, with reference made to some specific projects of the same kind.

2.3.1. The Behaviour Based Approach

The elastic behaviour of building materials is utilised in a plethora of vernacular architecture construction methods. The ‘Encyclopedia of Vernacular Architecture’ refers to such structures as tension arch systems. However, the ‘Review on Bamboo Structures’ provides a precise differentiation between tension and compression rods which are curved.

Even in opposing cultures and countries which may be on the completely opposite side of the world, examples of shell and arch structures that are elastically formed can be seen. Surprisingly, when considering the differences in countries and cultures, similar structures can be viewed due to the fact that the construction methods were developed empirically, with the basis being the elasticity found in the construction materials. Examples of this can be seen in the Southern Iraqi Ma'dan Mudhif Cane Huts (Lienhard et al, 2013), seen in the sample title B1 in Figure 2-2, and in Figure 2-3 on the left image. The mentioned examples are structures that are permanent and utilise reed bundles, which are fixed vertically into bucket foundations before being connected at a later time to the top, to form elastically bent arches.



(a) (b)
Figure 2-3: a) Mudhif (B1), b) Atabay Yomut. (Lienhard et al, 2013)

Mobile or temporary shelters utilizing construction systems that are bending active is another considerably common application. Some representative examples of this can be seen in the case of the tents used by Middle Eastern nomadic tribes. The construction of these tents is completed by the utilisation of partially bent wooden rib skeletons which each member act independently, combining with a surface constructed of goat hair felt or vegetable fibres. These are the basic elements needed in the construction of a number of differing lightweight structures, which can be deployed rapidly and propose a packing volume that is minimal. An example of this can be seen in the Iranian Kantuk or Kutuk, which uses the ribs of data palms as frames or arches to traverse via cane stringers and finally has a cane thatch applied as a cover. This example can be

seen in B2 of Figure 2-2 (Gengnagel, 2005). A further example can be seen in the Afghan Turkmen ‘Yomut’, as well as the Mongolian Yurt (Lienhard et al, 2013). Both of these structures enforce a pantographic grid which is bent for the wall skeleton, and in the case of the ‘Yomut’, bent elements are enforced in the construction of the roof. This can be viewed in sample B3 and on the right hand side of Figure 2-3. Even in the advanced times of today, numerous differing examples of bending active structures have been predicted with the use of the Behaviour Based Approach. An example of a structure which is built in this manner can be seen in Vo Trong Nghia’s (Nghia, 2007) substantially large bamboo structures, which sit next to a plethora of gridshell and arch structures constructed with living willow stems or green wood (Ludwig, 2009).

Presently, designers and architects alike are pursuing an increasing interest in the use of the advantages of polymers as a way of facilitating active bending in a number of different kinds of small pavilion structures and conceptualized installations. As presented in Figure 2-4, the 2006 structures ‘The Loop’ (Projects12, 2013) and the ‘Elastic Habitat’ highlighted an avid awareness in the interest of creating in situ shapes that are complexly curved.



Figure 2-4: a) The Loop, New York (2006), b) Elastic habitat Saint-Etienne (2006) (Lienhard et al, 2013)

2.3.2. The Geometry Based Approach

The intense, lightweight structure research of the previous century results in a magnified interest in surface shells and gridshells, which are double curved. However, large elastic deformations were unable to be simulated at the time as the simulation

techniques had only just started to be developed. The hanging model is considered the most widely recognised and popular method of form-finding, this method could be handled not only in an experimental way but also as an analytically. The similarity between the elastic curve and the hanging chain has additionally been proved in experimental tests (Gas et al, 1985).

It was during the 1960s that Frei Otto commenced intensive gridshell research (Hennicke, 1974). Following a small number of prototype structures came the construction of the 1974 ‘Multihalle Mannheim’, the first large span gridshell in the world (Happold & Liddell, 1975), presented in section G2 of Figure 2-2 and in Figure 2-5 on the left-hand side. To this date, only a handful of gridshells that further develop this approach have been constructed. One such structure which resembled Frei Otto’s structure is the ‘Hooke Park Workshop’ of 1990 (Hennicke, 1974) (G3 in Figure 2-2). Although not a gridshell as such, the method of construction of this model was similar to Otto’s approach in that a set of timber arches were elastically bent, and of which the basis was derived from hanging model studies. It was these developments that resulted in the construction of the more recent 2002 ‘Downland Gridshell’ (Figure 2-5(b)) (Harris et al, 2003), and in De Groot’s 2007 Savill Garden Gridshell (Harris et al, 2008).

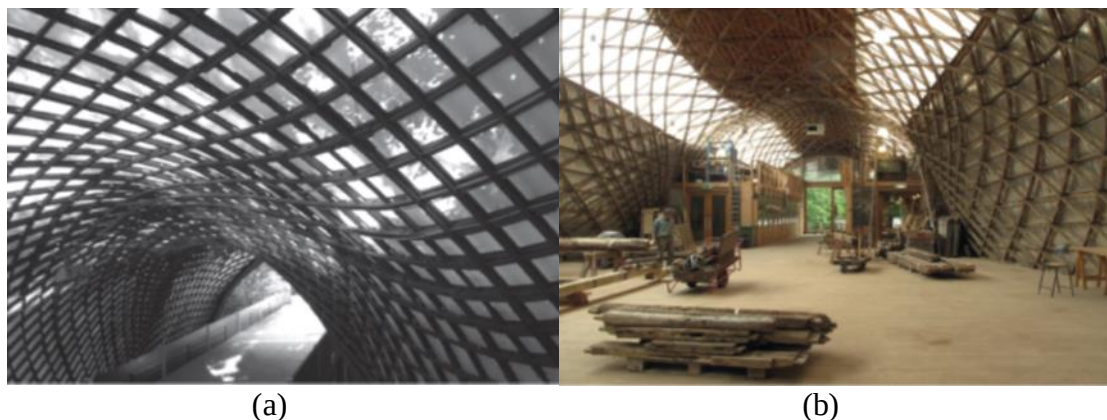
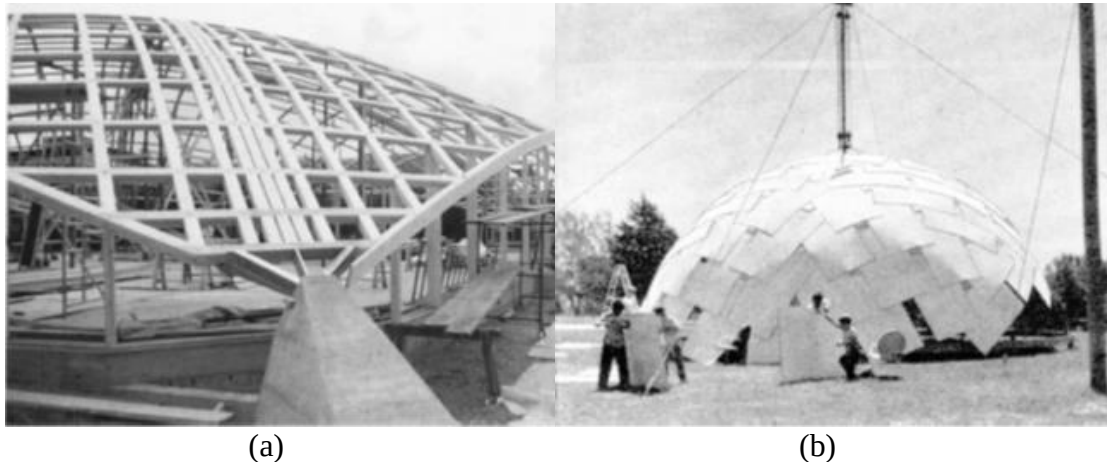


Figure 2-5: a) Multihalle Mannheim 1974 (G2), b) Downland Gridshell 2002

Further examples of gridshells that make use of the elastic properties in timber in order to create the given analytical geometry through the bending of the grid are the ‘Polydôme’ of 1991, presented in Figure 2-6(a) (Natterer & MacIntyre, 1993). This

structure utilised timber which was multi layers in order to shape the sphere's geometry. Other examples include the Expo 2000 'Japanese Pavillion' (Jodidio & Ban, 2010), which used spheres of cardboard, and the Helsinki zoo tower (Salokangas, 2003) that allowed geodesic lines to be traced by the grid on a surface that was free form. However, the projects mentioned automatically lost their advantage of an erection procedure that is easy and an automatic position setting geometry due to the essential stage of controlling the structures final geometry during the process of erection.

Buckminster Fuller introduced a unique approach in the construction process of surface-shells in his geodesic dome study, in which he developed the Plydome Structures of 1957 (Gorman, 2005) presented in section G1 of Figure 2-2 and Figure 2-6(b). In this case, a sphere can be seen as defining the global shape, and panels of plywood are mainly bent around a single axis before being interlinked at the geodesic dome's topological points.



(a) (b)
Figure 2-6: a) Polydôme 1991 (Natterer & MacIntyre, 1993) b) Plydome 1957 (G1) (Gorman, 2005)

2.3.3. Behaviour Based Geometry (Integral Approach)

Simulation techniques have now advanced to such an extent that they facilitate the analysis and form-finding of structures that form their curved, complex geometry singularly via the process of erection, during which their elastic deformation takes place. This has therefore been used as a basis for several investigations which include fresh types of gridshells and surface-shells, as well as structural bent components which

use membranes as a system of restraint, membranes possessing elastically bent battens, and numerous different types of elastic/adaptive kinetic structures.

Numerical form-finding methods are significantly challenged by the elastic beam integration into a surface that is form-active for the creation of structures that are significantly lightweight and are primary structures that have been integrated into membranes that are mechanically prestressed. The work titled “Spline Stressed Membranes” (Adriaenssens, 2008) has recently paid heed to such hybrid structures, where the motivator behind this work was the aforementioned membrane structure for the Expo Seville in 1992, which demonstrated the integration of beams with a curved tensegrity (Barnes et al, 1996). A structure titled the self-descriptively as the “Bat Sail” (Off, 2010) demonstrates some prototypical work on this phenomenon. Built in 2011, the hybrid “Bat Sail” structure featured a 12 metres funnel shaped membrane umbrella. The 7.5 metres long prestressed membrane using the fibre glass rods formed elastic bending, which is presented as a courtyard shading for a school of architecture in Marrakech, Morocco (Lienhard, 2012). Although “M1 Project” was the “Bat Sail” shape at the La Tour de L’Architecte in 2012 demonstrates the traditional membrane shape as the extended potential of form-active and bending active structures, presented in section BG1 of Figure 2-2 (Lienhard et al, 2013).

The Research Pavilion ICD/ITKE was built in 2010. In this case, it was the subsequent coupling of the planar plywood strips that were resulting in the 4m span arch, which was self-equilibrating. Real shell properties were developed in the structures load-bearing as a result of the interconnection and radical arrangement of the arches; this resulted in the concluding torus-shaped design. The given connection points were the control system in the structure’s final geometry due to the fact that the form-finding of the structure was based on the erection simulation (Lienhard et al, 2010), presented in section BG3 of Figure 2-2 and Figure 2-7(b).

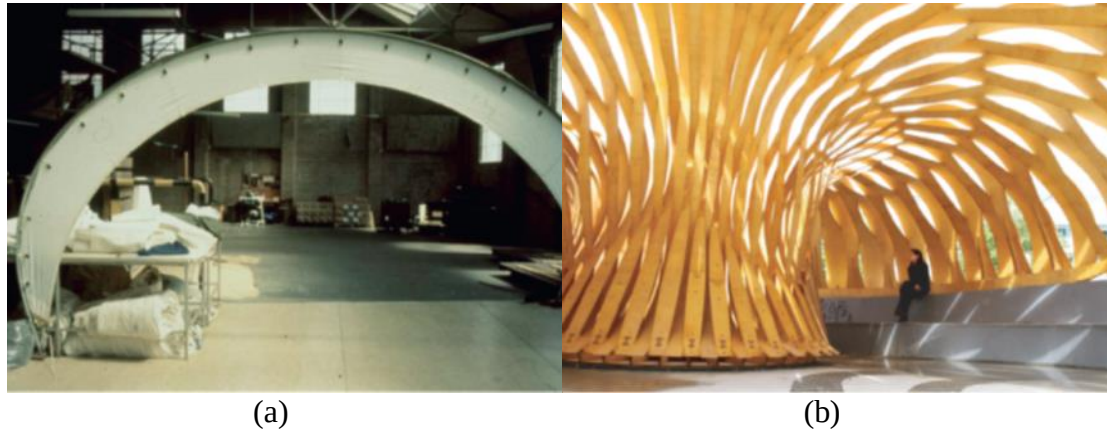


Figure 2-7: a) Membrane restrained arch (BG2), b) Research Pavilion ICD/ITKE 2010 (BG3) (Lienhard et al., 2013)

In the past decade, numerous studies have concentrated on methodologies that enable the generation of developable grid configurations which allow for the simulation of the subsequent geometry that ensues after the process of erection (Li & Knippers, 2011) (BG4). It is the process of shaping in which members of the grid are elastically bent on a gradual basis that results in the ultimate geometry of gridshells which are highly elastic. In order to obtain this, many form-finding methods have been developed which enable the reproduction of the process of erection. The studies of today place a high aspect of analysis upon these said structural effects, in the case of numerous, varying grid configurations and surface geometries. Additionally, it should be noted that the use of NFRP's presents an environmentally friendly substitute in the construction of gridshell structures (Gengnagel, 2011).

The AA in London generated a visionary project in 2002, known as the 'Hybgrid2' (Menges, 2004) is an adaptive gridshell structure possesses three layers of GFRP lathes, which have been curved locally (BG5). Active bending could be enforced in adaptive structures due to the provision of suitable building material properties and the deformation process, which is reversible. Similar research was undertaken by the 'Hyberbody Research Group. IBA Hamburg's 2014 'Softhouse' was an adaptive façade, which operates a shading system, that incorporated the use of tensile members and boards of elastic GFRP in shape adaptive strips which were continuous (Lienhard et al, 2013).

2012 EXPO at Korea Yeosu saw the “Thematic Pavilion” unveiled, which was the first kinetic façade that uses elastic bending alone. In this kinematic media façade, a total of 108 GFRP lamellas were promoted, which controlled buckling constitutes the process of deformation. This results in the façade being able to adapt to light, as well as the physical conditions of the building, therefore enabling special lighting effects to be employed as a form of artistic staging. This structure has an overall length of 140 metres, with the height lying between 3 and 14 metres (Knippers et al, 2012).

Although the examples considered may be different in terms of their approach to design and the construction type, they all share one common factor; the use of building elements that are straight or planar for the creation of curved geometries. Hence, the common denominator between these structures is the process of formation, in which the elements were elastically bent, leading to questions that are similar in their addressing of form-finding, materiality and the planning processes. The continuous developments in simulation tools and new materials provide the suggestion that structures such as the ones presented are far from reaching the point of exhaustion in their respective application fields. Hence, new fields for the application of bending active structures can be introduced, with an increasing number of scientist’s committing themselves to the design, simulation and material research and development of bending active structures. However, by no means does this guarantee that such methods will replace the established building techniques on a larger scale. It is important to remember that all bending active structures rely mainly on the mechanisms of physical form-finding, which intensions of design must adhere to. Therefore, the more general field of application will remain a niche category in the wider view of construction.

2.4. Material Overview

In the 19th and 20th century, structural and geometrical variety was significantly limited since the basis for architecture was formed by a rigid set of structural and geometrical typologies, which, although where well defined, controlled the complexity

of the technology. Hence, it can be documented that only a small portion of widely recognised individuals at the time, including Antonio Gaudi and Vladimir Shukov, developed strategies to define from where forces and materials were the basis (Lienhard, 2014).

It is the work of the aforementioned architects, which in the 1950s resulted in a fresh interest in construction principles that are lightweight and alternative by architects and/or engineers such as Frei Otto, Félix Candela, Buckminster Fuller and Heinz Isler. It was the highly inter disciplined groups of engineers and architects who worked for the said individuals which provided a significant contribution to the development of structural concepts which are force and material informed. Hence, it is through the work of these architects and engineers that the development of form-finding techniques was enhanced, as such techniques were necessary to achieve the aforementioned developments. Therefore, the use of bending active principles started to gain attention in the construction world, with traditional materials such as bamboo and softwood becoming popular once more (as per the geometry based approach). Unfortunately, as a result of the huge amount of effort and time which is necessary for the planning, form-finding and engineering of such grandiose projects (such as the 1974 ‘Multihalle Mannheim), only a few influential projects were completed with the use of such construction principles. The wide spread consideration of structures that enforced active bending was prohibited until recently by the lack of engineering techniques that enabled the structural analysis and form-finding (Liddell, 2015).

Coinciding with the significant development of lightweight structures was the introduction of Fibre Reinforced Polymers (FRP). They were broadly introduced in the 1950’s material, which offered an inimitable ratio of high strength and low bending stiffness. The material was quickly utilised in the production of sporting goods such as golf shafts, pole vaults, and significantly the camping tent. Also, FRP’s were used by architects in non-structural to create geometries that were chiefly free form and to initiate the idea of modularized structures that were manufactured industrially. It is significant to note that in the case of building applications that are significantly more

industrially orientated, the low electrical conductivity and chemical durability of FRP's was the selling point. Monsanto Chemical Company's "House of the Future" (1954) and Suuronen's "Futuro" (1968) were the first architectural constructions where Glass Fibre Reinforced Polymer was the primary material. The formal appearance projected in these two examples suggested the use of high-tech technology in their construction, when, their curved surfaces were a result of manual lamination techniques, which needed intense labour. In 1975 Buckminster Fuller created the "Fly's Eye Domes", and it was after the creation of these structures that the use of GFRP declined, in some part due to the oil crisis of the time (Ananthasuresh, 2015; Akyürek et al, 2018).

There is a huge range of strength densities and stiffness in construction and building materials such as rubber which is compliant and steel which is stiff. It is the combination of properties that maybe considered the most important factor when finding materials appropriate for construction, rather than just one single aspect of mechanical behaviour. In the case of bending active structures, the variables of the highest importance are permissible bending stress and Young's Modulus. Ashby developed a useful method of rendering the materials which are adequate in a specific design task by creating diagrams that depict fields of material classes and sub fields on individual materials. 'Search regions' are defined in his diagrams which pinpoint the design spaces for specific applications (Ashby, 1999).

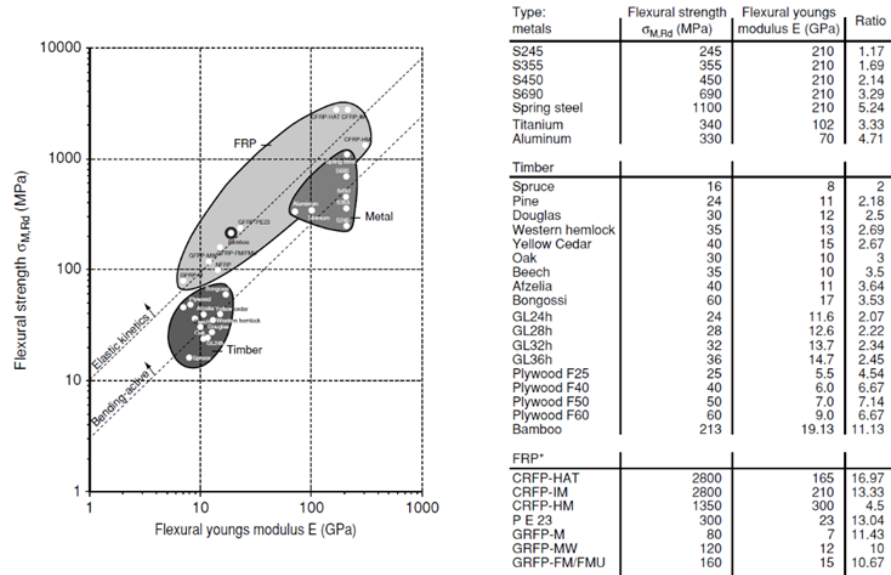


Figure 2-8: Common building materials with the ratio of strength σ_M (MPa) to stiffness E (GPa) (Ashby, 1999)

Selected materials should have a high breaking strain to ensure that an adequate capacity of load-bearing is guaranteed in a structure that incorporates significant bending-stress. Many traditional building materials possess these properties, such as reed, bamboo, and softwood. Hence, this has resulted in active bending being a highly utilised feature in vernacular architecture throughout a broad range of continents and cultures. Such structures were predominantly and typically discovered in locations where either softwood was the only material available or wood was rarely found, or in cultures where technology was lacking for the processing of bigger pieces of timber. Therefore, this is strong evidence of the economic material use and lightweight potential of bending active structures.

Nowadays, the industrial processes of manufacturing used for FRP products are semi-finished (such as pultrusion), which results in the guarantee of consistency of mechanical behaviour and makes them more economical. In 2012, the first products made of GFRP were granted approval, a form of national technical approval, in Germany, for use in construction projects. This was an importance achievement of significant, which was long anticipated in the jump from research labs to use in the building industry, and particularly in the bending active technique. One example of a

building that took this step can be seen in the “Softhouse” of 2013, which was presented at IBA Hamburg and utilised a shading system with an adaptive façade (Lienhard et al, 2013).

Figure 2-8 presents a variety of common building materials. Based on the ‘Ashby Diagrams’, the figure shows the materials listed and plotted on a graph, alongside their respective flexural strength to stiffness ratios (Ashby, 1999). In the context of building structures, the values shown in the graph are extracted from DIN 1052:2004-07-08, DIN EN 1993-1-1:2004 and 1999, and DIN 17221. Using built example’s experience as a basis, materials that are sufficient for use in bending active structures provide a ratio of:

$$\int M \cdot \frac{Rd}{E} > 2.5 \quad \text{Equation 2-1}$$

Which $\int M \cdot Rd$ [MPa] and E [GPa]

Permissible permanent elastic stress is limited in elastic kinetic systems due to the essential need for fatigue control. Therefore, the following ratios are needed:

$$\int M \cdot \frac{Rd}{E} > 10 \quad \text{Equation 2-2}$$

With the inclination of $\int M \cdot Rd/E > 10$ as an indication, different groups can be derived by separating the different materials.

In addition to this, the long-term behaviour of a structure must be given significant consideration. In structures that are bent, the system’s integrity is likely to be relatively unaffected by creep deformation and the prestress loss. Where prestress does not play a pivotal role in the stiffness of the system, it is feasible to choose an adequate material. Kinetic structures which are elastic and adaptive also rely heavily upon long-term behaviour, which is advantageous in that it enables the cyclic exposure of elastic deformations, which are large, as well as the advantages of low bending stiffness alongside a high strength of material’s yield point. It is also notable that it is only if no permanent creep deformation occurs that the resetting effect can be exploited. In this case, certain types of Fibre Reinforced Polymers (FRP) can deliver the required material behaviour.

In bending active structures, it is implied by the design, that specific types of timber, as well as FRPs, are adequate materials, but in the case of elastic kinetics, the requirements will only be fulfilled with the use of FRPs and bamboo. The resetting effect could only be used in the case of there being no permanent and long-term creep deformation. In this case, the material behaviour required could be met by FRPs. The mechanical properties and behaviour of FRPs, as opposed to steel reinforced materials, thus needs to be understood prior to designing structures using such reinforcements.

There are number of advantages that FRP boasts in the construction field, such as low lifecycle costs, low thermal conductivity, nonconductive, corrosion resistant, high in strength yet lightweight, dimensionally stable, impact resistant and electromagnetically transparent. However, despite the advantages associated with the use of FRPs, several disadvantages exist like susceptibility to fire (without insulation) and mechanical damage, poor shear strength, the slightly high initial cost, longer load transfer (Lap) lengths.

Table 2-1: FRP's Design Properties (Ando, 1998)

Reinforcing Material	Yield Strength ksi (MPa)	Tensile Strength ksi (MPa)	Elastic Modulus ksi (GPa)	Strain at Break Percent
Steel	40-75 (276-517)	N/A	29000 (200)	N/A
Glass FRP	N/A	70-230 (480-1600)	5100-7400 (35-51)	1.2-3.1
Basalt FRP	N/A	150-240 (1035-1650)	6500-8500 (45-59)	1.6-3.0
Aramid FRP	N/A	250-368 (1720-2540)	6000-18000 (41-125)	1.9-4.4
Carbon FRP	N/A	250-285 (1720-3690)	15900-84000 (120-580)	0.5-1.9

Glass fibre constitutes the predominant reinforcing fibre in FRPs, with the most commonly utilised fibre being electrical glass (E-glass). The reason for this is that E-glass has a number of benefits, such low material cost, possessing ample resistance to heat and possessing high electrical insulation properties. Structural glass (S-glass) fibres possess higher levels of tensile strength and heat resistance than E-glass. Perhaps the strongest GFRP is the speciality Alkali resistant glass (AR-glass) fibre; however, speciality fibre has a much higher cost than other GFRPs, and thus may not be commonly used. Basalt Fibre Reinforced Polymer (BFRP) may be preferred to E-glass fibres due to the higher tensile strength possessed at a similar cost to E-glass. However, while BFRPs may have a higher tensile strength than E-glass, this strength is much lower found in S-glass. Aramid fibres (AFRP) are characterised by high strength, high elastic modulus and a lower density (roughly 40%) than glass fibres. Aramid fibres are higher in cost than basalt fibres and glass fibres, however, meaning that they are less commonly utilised in structural applications due to the low compressive strength possessed (perpendicular to the direction of the fibre). Additionally, aramid fibres are renowned for absorbing water easily. This means that it is critical to carefully plan storage and projects that utilise aramid fibres. Aramid fibres are often used in ballistic resistant textiles as the impact is absorbed well by the fibres (Ando, 1998).

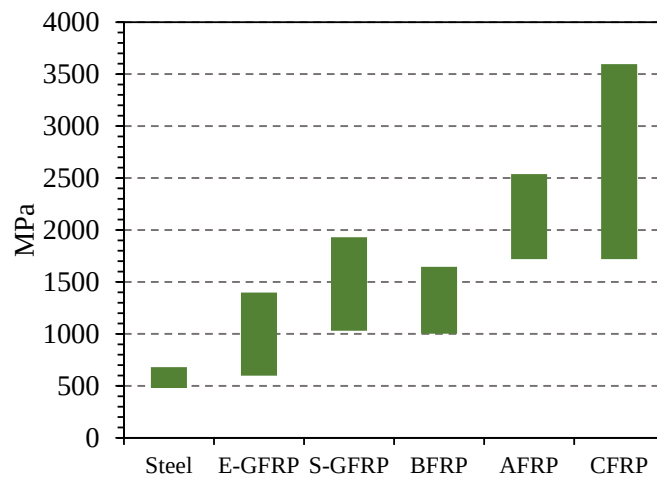


Figure 2-9: Comparison of FRP Tensile and Steel Yield Strengths (Ando, 1998)

2.4.1. Creep-Rupture Stress Limit

It is very important to understand the limits of materials used in the long-term loading resistance when making decisions about the specific reinforced composite to utilise in structural applications. If FRP is subjected to cyclic and continuous loading in excess of its load resistance ability, then fatigue failure, long-term deflection and/or creep rupture may occur in the structure. Thus, the creep rupture stress limit must not be breached by the evident stresses in FRP reinforcement (Benmokrane et al, 2019). Consequently, the reason which design codes such as the ACI purport a reduction factor to be applied to FRPs ultimate tensile strength. The following table notes the reduction factors purported in the relevant ACI codes for the different FRPs considered in this research.

Table 2-2: Creep Rupture Reduction Factors (Ando, 1998)

Material	GFRP	BFRP	AFRP	CFRP
Creep Rupture Stress Limit ($F_{f,s}$)	0.20	0.20	0.30	0.55

The useable strength of a system of FRPs is significantly impacted by creep rupture reduction factors. The following graph depicts the range of tensile strength in various FRPs. CFRPs possess a higher useable strength subsequent to the application of the reduction factor. Greater useable strength is also associated with reduced levels of FRP.

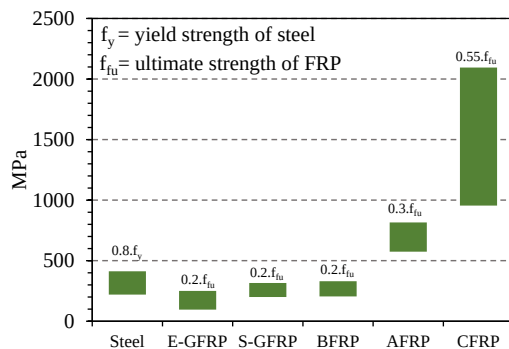


Figure 2-10: Factored FRP Tensile Strengths

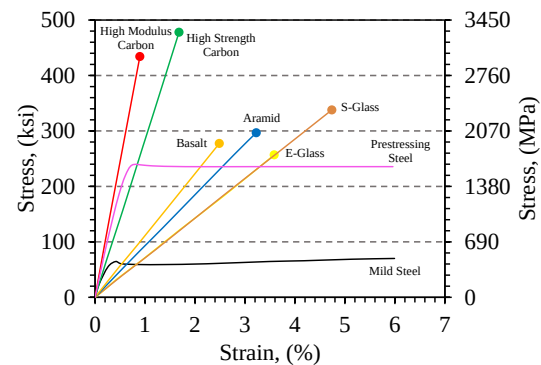


Figure 2-11: FRP Materials properties

2.5. Temperature impact

Contemporary civil engineering structures are designed to be both durable and sustainable, lasting for long periods of time ranging from 75 to 100 years of service life. To obtain the strength reduction factors for design purposes, the performance behaviour of constituent materials and their bond behaviour under environmental temperature impact is required. The same can be said for FRP composites, and particularly GFRPs which gaining exposure for their use in structural applications. Despite this, valid and comprehensive data with regards to FRPs durability remains unknown. The primary difference between new materials, such as composites compared with conventional materials, such as concrete or steel, is the lack of information related to their long-term performance, especially under particular circumstances. When studying the durability of FRP composites, many different environmental agents affecting the material can be studied such as moisture uptake, sustained stress, temperature variations and UV radiation as the most common factors. The most severe threat to FRPs, relates to temperature changes identified as Freeze-thaw exposure by the Civil Engineering Research Foundation (CERF) and the degradation tends to be exacerbated by moisture absorption (Lorenzo et al, 2018).

Many researchers are investigating the impact of severe environmental conditions on the physical and mechanical behaviour of FRP composites. Perhaps one of the focal points of FRP properties lies in the high durability that such materials possess in environments that may be described as relatively harsh. Sousa investigates the effects of thermal cycles from -5 to 40 °C for up to 190 cycles on the mechanical response of pultruded GFRP profiles (unsaturated polyester-UP/vinyl ester-VE) (Sousa, 2016). Viscoelastic properties did not degrade, tensile and interlaminar shear properties changed only slightly (UP-10% and VE-13%), but flexural properties suffered a significant loss (UP 24% and VE 25%). Similar behaviour found by Dutta, who tests glass-epoxy FRP samples in dry air freeze-thaw cycling from -40 to +23 for 150 cycles and determined a reduction in tensile strength by 10%. As thermal cycling introduces failures such as matrix microcracking as well as adhesive rupture, e.g., fibre matrix

debonding, matrix dependant properties like stiffness are expected to degrade faster than those dominated by the fibre's performance (Dutta, 1988). Wu discussed the durability of unloaded and pre-strained GFRP (VE) composite bridge deck face sheet coupons under freeze-thaw (4.4°C to -17.8°C) and low temperature (constant -17.8 °C) conditions in media of dry air, saltwater and distilled water for an ageing period of 625 cycles (~1250h). No statistically relevant changes in the flexural strength were recorded. Varying the cycling length (2 hours and 5 hours) had no measurable impact, assuming that the total number of cycles induces greater deterioration than the total exposure time (Wu, 2006). Similar behaviour was established by Tam, who tested CFRP and GFRP samples at dry air under F/T, sustained loading and combined exposure. Although strength and stiffness degradation occurred for CFRP laminates (up to 13% degradation), GFRP specimens were virtually unaffected (<3%). Moreover, other researchers have found a greater and more deleterious trend when superposing F/T with moisture (Tam, 2008). Karbhari investigates FRP (VE) laminates at different temperature levels at dry and wet conditions and found that low temperature thermal cycled samples deteriorate faster than exposed to constant immersion at sub-zero temperatures. It was concluded that moisture absorption causes participation and hydrolysis of polymer chains, resulting in greater molecular mobility hence enhancing the material deterioration. These chemical reactions are accelerated by micro cracks in the resin that happen at lower temperatures that facilitate the water ingress at higher temperatures (Karbhari, 2003). The collected water, in turn, expands at sub-zero temperatures and leads to additional matrix fibre debonding. Hollaway further established that sustained loading during the conditioning process reduces the durability of the composite, which was also found by Gibson, who established the moisture (Hollaway, 2010; Gibson, 2006).

Dutta investigated the effects of thermal cycles on the flexural properties of two types of GFRPs. The laboratory review has been carried out on the effects of extreme temperatures (less than 0 ° C) and freeze-thaw cycles on the mechanical properties of polymer composites. Two types of GFRP which were constructed from S2-glass and

E-glass fibres, were considered. The initial mechanical properties of these materials are shown in Table 2-3. Each of these samples was placed under three temperatures below zero degrees Celsius and freeze-thaw cycles of -60 to +50 degrees Celsius (Piyush et al, 1996). The E-glass samples developed enormous cracking after 100 cycles; therefore, no further testing was conducted. Whereas following 250 cycles showed no ostensible signs of degradation recorded on the S2-glass samples and so carrying on testing leads to minor degradation of 6.2% in the tensile modulus and 6.3% in shear modulus. Also, the post-cure phenomenon accelerated due to the high extremes of temperature used during temperature cycling, whilst the lower bound temperature would induce significantly high thermal stresses within the samples, which would combine to exceed their tensile strength. (Piyush et al, 1996; Grammatikos et al, 2016).

Table 2-3: Test materials and specifications (Piyush et al, 1996)

Name	S2-glass FRP composite	E-glass FRP composite
Process	Vacuum bag	Pultrusion
Fibre	S2-glass	E-glass
Matrix	Polyester	Polyester
Density (g/cm ³)	1.890	1.971
Volume fraction of fibre	0.532	0.593
Length (mm)	330.2	330.2
Section (wide – mm)	Square	Square
Thickness	12.7/19.1/44.5	127/38.1
Test span (mm)	254	254
Test temperatures (°C)	27, -5, -40 & -60	27, -5, -40 & -60
Thermally cycled	250	100
Thermally cycled (number & range)	-60°C to +50°C	-60°C to +50°C

Hui Li investigated research on the freeze-thaw resistance of unidirectional glass (GFRP), carbon (CFRP), and basalt (BFRP) fibre reinforced polymer epoxy wet layups from -30 to 30°C in dry air (Li et al, 2011). The thermal coefficient mismatching of the fibre and resin matrix may bring in debonding, micro cracks and even macro cracks of

FRP plates, so writers used embedded optic fibre bragg grating (FBG) sensors, which were applied to monitor the variation of the internal strain during the freeze-thaw cycles, to evaluate the internal stress inside the FRPs possible degradation mechanisms, also to estimate the coefficient of thermal expansion (CTE). With the CTE values, the stresses developed in the matrix of the FRPs were calculated. The freeze-thaw cycle showed a negligible effect on the tensile properties of both GFRP and BFRP. In addition to the above mentioned, tensile tests were conducted to illuminate the mechanical property degradation of the FRPs due to the freeze-thaw cycles. One freeze-thaw cycle lasted 24 hours and included a freezing state for 12 hours and a thawing state for the other 12 hours. The temperatures were set as -30°C in the freezer and 30°C in the oven with average freezing temperatures -27.3 , and the thawing temperature of 32.7°C as illustrated in Figure 2-12 over 90 cycles. The tensile properties of the unidirectional FRPs were tested according to ASTM D 3039 with a tensile speed of 2 mm/min. Results presented in Table 2-4 (Li et al, 2011).

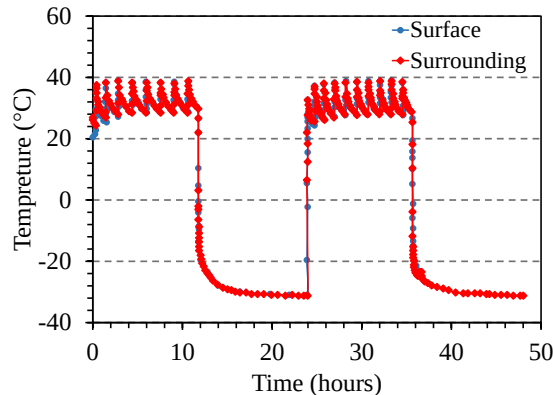


Figure 2-12: Evolution of the temperature with time during the freeze-thaw cycles (Li et al, 2011).

Table 2-4: Tensile Properties of the Cured Two Layers of FRP Wet Layups (Li et al, 2011).

FRP composite	Tensile Strength (MPa)	Tensile Modulus (GPa)	Elongation at break (%)
CFRP	971.4 $\pm$ 7.7	83.3 $\pm$ 7.7	1.12 $\pm$ 0.2
GFRP	517.9 $\pm$ 21.4	26.0 $\pm$ 3.8	2.04 $\pm$ 0.34
BFRP	602.9 $\pm$ 29.2	29.7 $\pm$ 2.8	2.2 $\pm$ 0.22

The temperature for the estimation of CTE illustrated in Figure 2-15. The freezing temperature, the equilibrium temperature at zero strain and the thawing temperature were tested as -27.3, 12°C, and 32.7°C (Li et al, 2011). The weight reduction for both specimens, CFRP and GFRP, was about 0.1 per cent after 60 cycles (Figure 2-14). The effect on the tensile modulus and strength were negligible for both the BFRP and GFRP samples. After 90 freeze-thaw cycles, the changes of the tensile modulus and strength on both BFRP and GFRP samples were insignificant. The changes in tensile strength, tensile modulus and elongation at break of FRPs due to freeze-thaw cycles illustrated in Figure 2-13.

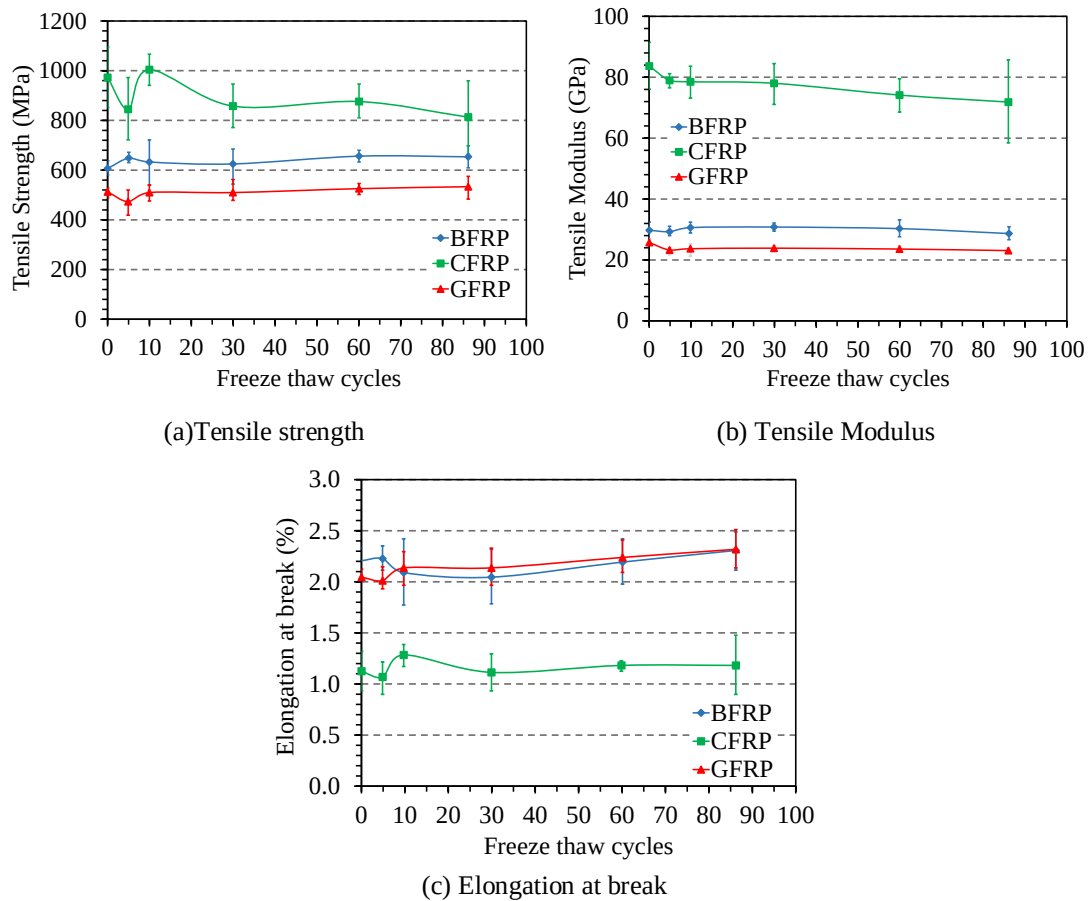


Figure 2-13: Effect of the freeze-thaw cycles on FRPs (Li et al, 2011)

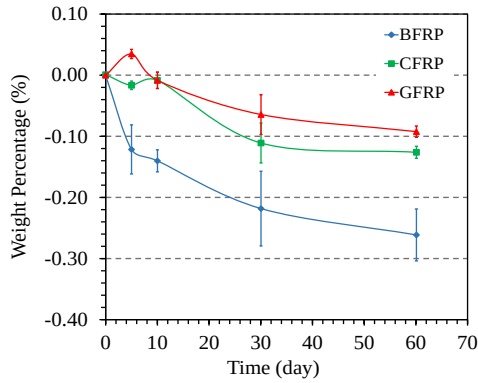


Figure 2-14: Weight changes of the FRP samples in 60 days (Li et al, 2011)

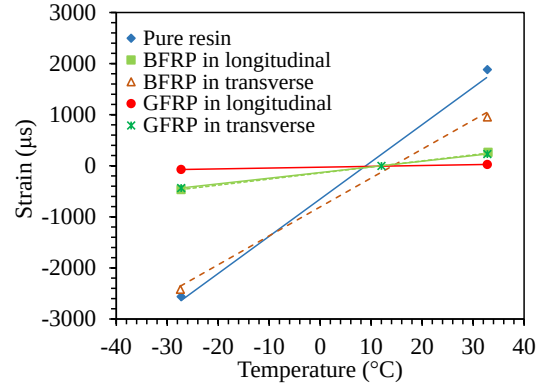


Figure 2-15: Linear fitting of the strain versus the freeze-thaw (Li et al, 2011)

Jia-Wei Shi, in 2014, carried out an experimental investigation of the freeze-thaw (FT²) resistance followed by tensile testing to investigate the effect of temperature on mechanical properties of FRP. Four different types of FRPs, such as hybrid FRP sheets, CFRP, BFRP, and GFRP were considered to carry the test (Jia-Wei Shi et al, 2014). Testing samples with sustained loading were conducted to investigate the tensile properties of FRP sheets up to 300 FT cycles.

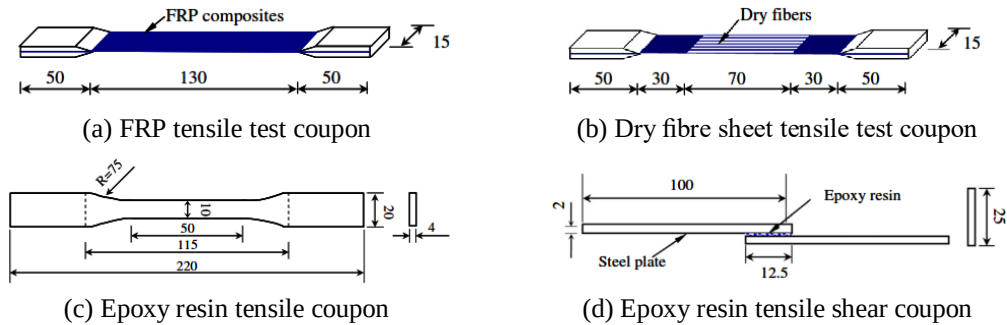


Figure 2-16: Test samples (coupons), for samples with 230 mm × 15 mm (Jia-Wei Shi et al, 2014)

The sustained loads applied to the FRP composites for GFRP and BFRP were 30% of the ultimate load 40% of the ultimate load for CFRP.

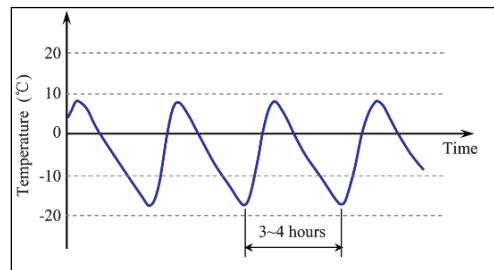
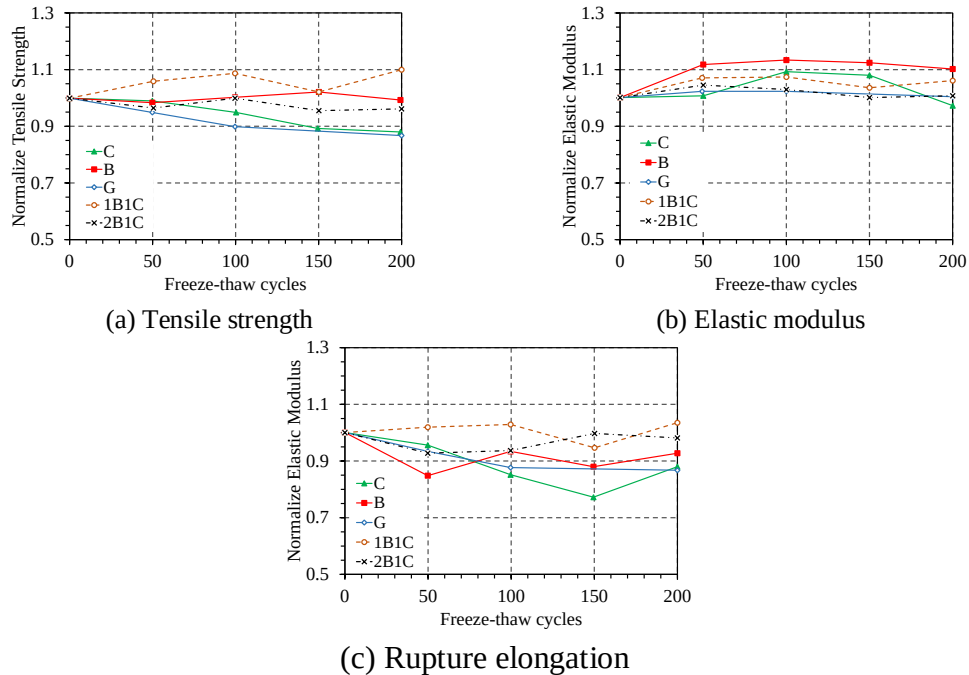


Figure 2-17: Temperature fluctuations during freeze-thaw tests (Jia-Wei Shi et al, 2014)

Table 2-5: Tensile properties of the materials at room temperature (Jia-Wei Shi et al, 2014)

Specimen	Material	Nominal thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Rupture elongation (%)
C-R	CFRP	0.111	4067±309	239.8±5.5	1.74±0.09
B-R	BFRP	0.156	2077±86	80.2±1.5	2.68±0.01
G-R	GFRP	0.198	1376±121	69.8±5.8	1.99±0.08
1B1C-R	HFRP (1B/1C)	0.267	2482±92	144.6±6.5	1.74±0.05
2B1C-R	HFRP (2B/1C)	0.423	2213±110	124.3±0.5	1.84±0.05

From Figure 2-18 (a) can be obtained, with the increase in the number of FT cycles, CFRP and GFRP sheets' tensile strength decreased. Also, an approximately 10% increase in the elastic modulus indicates that FT cycling can make FRP composites more brittle. With the increase in the number of FT cycles, the rupture elongation decreased in the three FRP sheets. A negligible effect was conducted on the tensile properties of BFRP and carbon-basalt hybrid FRP sheets under cyclic loading. Also, a 14% reduction in tensile strength captured over 200 FT cycles for GFRP (Jia-Wei Shi et al, 2014).

**Figure 2-18: Normalized tensile properties of FRP and hybrid FRP composites versus freeze-thaw cycles (Jia-Wei Shi et al, 2014)**

Along noteworthy researches conducted to investigate the effect of temperature on FRP composites, still the effect of temperature on composite materials which subjected to bending active is unknown. In this research an attempt will be conducted to investigate the effect of temperature on GFRP samples under two type of target temperature loading and cyclic temperature loading.

2.6. Aerodynamic behaviour

In designing structures, two main objectives safety and serviceability are a primary requirement especially with lightweight materials. Experimental testing and numerical simulations are two ways of assessing wind effects. Presently, the most authoritative way of assessing wind loads on structures is wind tunnel testing. However, the downscaling structures, especially thin and light structures, creates a considerable challenge to wind tunnel experts. Interaction between wind and structure is an important consideration in the design of many structures, particularly when the structure requires flexible and light properties. Such structures are generally susceptible to dynamic wind actions (Yang et al, 2010).

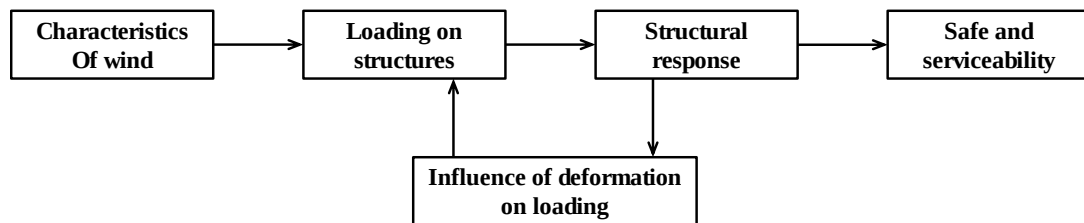


Figure 2-19: Schematic diagram for the design of structures for wind effects (Simiu & Scanlan, 1996)

Lightweight structures due to low damping and frequency are exposed to high deformation and displacements. Therefore, estimation of wind load presents on their so as one of the important effective parameters in designing such structures. Arch shaped roofs are becoming more requested due to their functionality purposes with large unobstructed clear spans (e.g., entertainment centres, exhibition centres, sports arenas, hangers, and so on) which can spring either from the ground or at an elevated level.

Sun using wind tunnel experiments investigated the wind pressure effect on ridge valley tensile membrane structures. To investigate the effects of wind direction, rise to span ratio, eave's height and terrain roughness were experienced in wind tunnel. Results obtained provided that wind direction and rise-span ratio have a great effect on mean wind pressure. Additionally, to measure the effects of wind direction and rise-span ratio, the peak wind pressure coefficients were calculated (Sun et al, 2019).

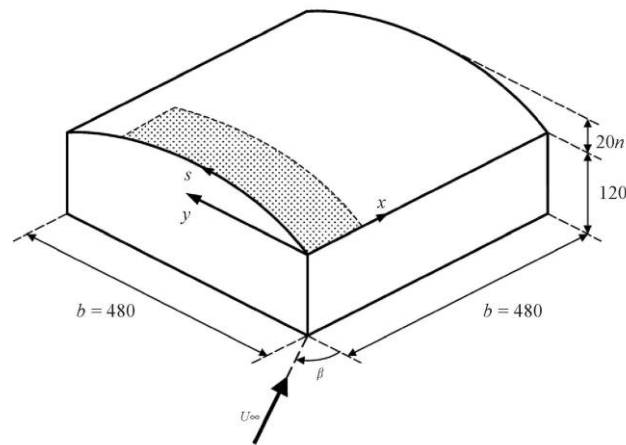
Abraham et al presented in 2013, the pressure coefficient distribution trends for the regions of centre half and leeward quarter has been similar to various national/international codes of practice. To study the wind pressure on curved roof structures with open and closed sides, wind tunnel pressure measurements were carried out for both open and suburban terrains condition. Results present the mean pressure coefficients obtained on the model with span ratio of 0.29 were higher than the values obtained for models with span ratios of 0.0 and 0.15 (Abrahm et al, 2013).

In low-rise buildings, aerodynamic characteristics are dominated by arch vortices. This means that the type of surface pressure distributions in low-rise buildings are similar, particularly in situations where the wind is evident along the roof ridge. Where wind direction is normal to the roof ridge, the arched roofs with a rise to span higher than 0.25 will exhibit positive pressures in the upstream region of the approaching flow. Larger structural responses may be caused by positive and negative pressure exerted at the same time with different portions. Serious wind loading appears to be found only in the wind direction closely normal to the ridge of the roof when comparing with the estimated equivalent static wind loading from experimental data. Thus, the careful consideration of wind loading and suitable wind tunnel testing measure is required when considering wind loading. Although the shape of curved roof and bending active structure could look similar, but as the created curve due to bending active is a form finding procedure, it is worth to investigate the impact of lateral force on open and closed models and various ratios on bending active structure.

Franchini studied a scale model of 1:200 of an industrial structure (coal shed) with the multi-segmental curved roof is fabricated using acrylic sheets under simulated open

terrain conditions. The ceiling of the model was equipped with pressure valves on and below the roof for both models with and without end walls. The model was tested for different wind incidence angles from $\theta = 0$ to 360 degrees in steps of every 30 degrees. Experiments were also conducted for a number of alternative selected skew angles of wind incidence, such as $\theta = 45, 135, 225$ and 315 degrees. For wind direction parallel ($\theta = 0$ degrees) to the axis of the roof, the entire roof of the model was subjected to suction and high at the windward arch (a1) and gradually became low at the leeward arch (a8), especially for the model with gable end walls and this trend was being observed in the codal recommendations. In the variation of C_{pe} , for wind direction perpendicular ($\theta = 270$ degrees) to the axis of the roof observed, that a small portion in the windward region was exposed to suction as forecast by AIJ recommendations, high suction at the centre region and relatively low suction at the leeward region (which is also observed in many of the codal recommendations). The value of C_{pe} at the leeward quarter from various codes reasonably compare with the measured value. The pressure coefficient distribution trend given in International Standard were similar to the study, except the last 1/6th span at the leeward region. It was observed from the measurement that high suction on the roof occurred for a skewed wind incidence ($\theta = 30$ degrees) with a value of $C_{pe} = -1.433$, which was well above those that were realised with wind blowing parallel ($C_{pe} = -1.221$) or perpendicular ($C_{pe} = -1.118$) to the axis of the roof. Under $\theta = 300$ degrees wind flow angle, a maximum value of $C_{pe} = -1.09$ at the downstream of the apex of the centre arch (a4) was observed in the model with no gable end walls, whereas a maximum value of $C_{pe} = -1.433$ was found at the downstream of the apex of the arch (a1) in the model with gable end walls, at the same location (e.g., at $X/d = 0.75$ and $y/l = 0.56$). Also, for the skewed angle of wind incidence ($\theta = 300$ degrees), a maximum value of $C_{pe} = 0.282$ was observed at $X/d = 0.68$ and the value of C_{pi} (or C_{pe}) were moderately higher at arch (a1) when compared to additional arches for both cases, i.e., with and without gable end walls (Franchini et al, 2005).

The fluid behaviour of curved roofs is driven by the contention that at least one of the edges reaching the windward roof corner will be curved. Analysis scope is limited to roof geometries, where two of the edges of the roof are straight lines. The straight edge vortex behaves as the flat roof case, while the curved edge vortex behaviour was affected by the curvature of the roof. For large wind angles, the behaviour of curved roofs was the same as flat ones. Conversely, for small wind angles, the conical vortex was formed close to the top of the curved edge if the curvature is large enough. Thus, pressure distribution near to the curved edge possesses a minimum at the windward corner solely when the angle of the wind is large enough; opposing this, minimum pressure will be achieved close to the peak of the curved edge (Franchini et al, 2005). According to the results of this study, angle of wind flow is a significant factor which is required to be investigated in a reasonable interval of angles.



Shadow area indicates the region where pressure taps are located. All dimensions are in millimetres

Figure 2-20: Sketch of the experimental configuration (Franchini et al, 2005)

The CSIR carries out a number of wind tunnel tests to measure wind pressure coefficients on catenary vault structures. The measurements' basic purpose was to evaluate the usability of the design data included in SANS 10160-3:2011 (SANS, 2011(b)). Four catenary vault roof geometries and a semi-circular shape was modelled and tested in a boundary layer that was nominal and that corresponds to the category of open terrain. The main purpose of such measurements was to assess the applicability of the design data used in SANS 10160-3:2011 (SANS, 2011), as well as to establish the

requirement for data development in relation to catenary vaults. Several experiments can be drawn from these tests, and several conclusions can thus be assumed. For catenary vaults measured in 3D flow conditions, a set of design wind pressure coefficients was established. These possess an aspect ratio (H/R) of between 0.8 and 1.6. Pressure coefficient distribution over the catenary vault with the lowest H/R ratios implies the highest degree of similarity with the circular form which was consistent with the SANS 10160-3:2011 (Sans, 2011). In terms of the steepest vault, the experimental data depicts the closest similarity to the duo-pitch data from this standard. The shallow catenary vault's (i.e., $H/R \leq 1.2$) critical orientation corresponds to $\alpha = 30$ degrees, whereas the highest vault (i.e., $H/R = 1.6$) corresponds to $\alpha = 0$ degrees. It is further established that a 1.2 H/R ratio constitutes the border case for the application of both circular data adopting approximations (i.e., $H/R \leq 1.2$) and that the duo-pitch data was more appropriate for $H/R > 1.2$. When adopting the 'duo-pitch data' (for $H/R > 1.2$), the catenary profile's average roof pitch (Ψ) was approximated as $\Psi = \tan^{-1}(H/R)$. Masonry vaults are widely considered as possessing a much larger magnitude and higher self-weight than the wind loading. Nonetheless, design may be governed by the wind effects of catenary shells that are not reinforced, and particularly this is exhibited in those shells possessing steep profiles (Sans, 2011). This study demonstrated a comprehensive way to evaluate the effect of wind on curved shape structure, and thus, an optimized approach is required to be proposed for wind investigation on bending active structure

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CHAPTER 3

METHODOLOGY

This chapter describes laboratory's methodology conducting in the structural laboratory and wind tunnel testing. Among the items within this chapter are the introduction of laboratories used in research, equipment used in the construction of laboratory structures and models, as well as the program of experiments performed.

3. Methodology

3.1. Introduction

In the structural action, different types of approaches were defined and presented in Figure 2-1. Bending active theory is the only approach that structural members have active energy stored due to initial bending, which leaves wide areas of potential research. This delivers an opportunity to investigate how the stored energy can be used for structure formation and affect the structural behaviour. Also, as it is applicable to various structures such as temporary constructions and building retrofit, it is helpful to give a better insight in bending active theory before the design and construction stage. To the best of authors' knowledge, there were limited studies investigating bending active theory, that their focus was on architectural aspect only or a specific design. The current research aimed to provide fundamental information of the structural behaviour of bending active structures which is helpful for researchers and designers. The research structure was developed and presented in Figure 1-1 to give a better insight of the structural behaviour of bending active structures under both internal stresses created due to bending and external loadings.

To study the behaviour of bending active components, such as stress distribution and deformation under various circumstances, it established a need to perform laboratory tests and constructing physical models. Considering limitations such as time, expenses and laboratory equipment availability, it was impossible to construct and test laboratory models for all desired scenarios during allocated time on this research, therefore numerical modelling was introduced to this research to enable further investigation. The simulation results were verified with the experimental results to assess the numerical models' reliability and accuracy. Based on the verifications, other factors such as geometries, loads, and materials were assessed numerically. As the temperature change has direct effects on the materials' properties, an investigation was required by applying temperature loading on the samples. Lateral force is a

considerable factor on structures especially in lightweight structures. Apart from the unique form fined geometry, elastic energy stored in bending active structures leaves unknown areas in the structural behaviour facing lateral force. To observe these behaviour, the effect of wind on open and closed bending active models were studied using wind tunnel testing. Finally, a mock-up was developed by the obtained findings to demonstrate the potential of new design concepts and understanding the manufacturing challenges.

The experiments performed in this research are presented in two separate parts. In the first part, the structural behaviour including stresses and deformations created due to bending and point loading were investigated. Besides, samples subjected to temperature loading (targeted and cyclic loadings) were studied through tensile testing as well as investigating the impact of temperature loadings on deformations and load bearing. In the latter, the behaviour of active bending structures against lateral force was investigated using wind tunnel laboratory.

Numerical modelling was used to simulate models under the same conditions and specifications as laboratory tests to validate the outcomes. Using ABAQUS software, numerical modelling was conducted to further investigate factors such as various geometries and f/L ratios, materials, and load bearing. Furthermore, ANSYS software was used to simulate the wind impact on the structures.

In the following chapter, the materials used and the principles of equipment, laboratory machinery, and modelling were presented. Additionally, the processes of testing were also explained in detail.

3.2. Materials

Glass Fibre Reinforced Polymer (GFRP) materials with low modulus of elasticity and high yield stress were selected to be used in bending active models due to its low cost, the ability of processing ample resistance to heat.

Materials used, as shown in Figure 3-1, were provided locally from *Engineered Composites Company*, specialised in the supply of high quality, maintenance free and

corrosion resistant GRP pultruded products. The circular and rectangular cross-sections are the most widely used in construction. In this study, circular section samples of GFRP with a 30 GPa modulus of elasticity, and rectangular cross-section (strip) samples of GFRP with a modulus of elasticity of 17 GPa were used. The details of samples' specifications were listed in Table 3-1.



Figure 3-1: Glass Fibre Reinforced Polymer (GFRP) samples

Table 3-1: Sample's Specifications

Cross-section	Cross-section dimensions (mm)	Elasticity Modulus (GPa)	Yield stress (MPa)
Circle-1	D = 7.9	30	550
Circle-2	D = 9.5	30	550
Strip-1	40 × 5	17	170
Strip-2	80 × 8	17	170

3.3. Experimental Tests

Tests to investigate the structural behaviour were performed in two separate categories of Bending and Loading tests and Wind Tunnel testing.

3.3.1. Bending and Loading Tests

The schematic graph of the laboratory procedure of bending and loading tests was shown in Figure 3-2. The equipment and machinery used in bending and loading experiments and the test procedure performed were further described in the following.

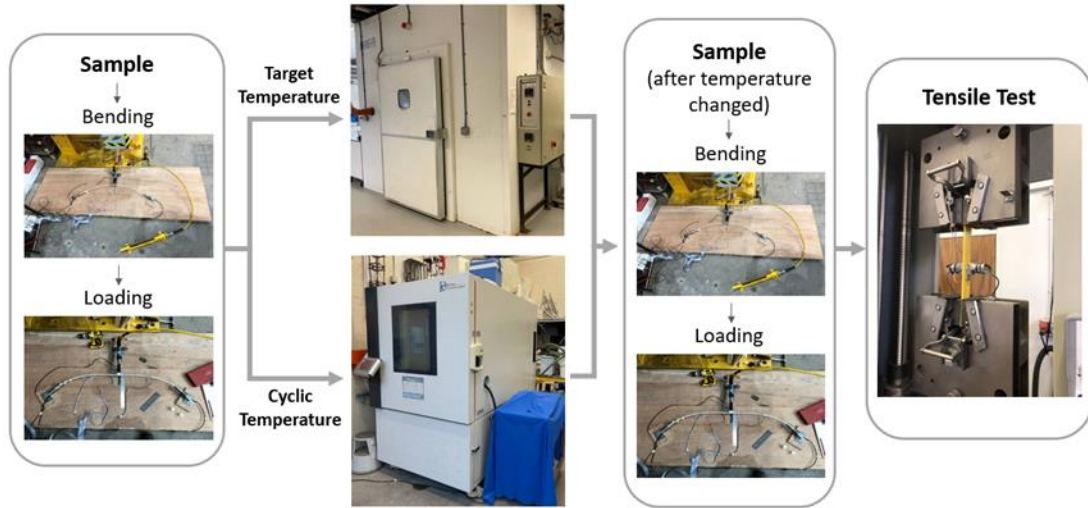


Figure 3-2: Experimental tests

3.3.1.1. Equipment

3.3.1.1.1. Strain Gauge

Mechanical measuring and testing are comprised of the need to understand an object's reaction to various forces. Strain refers to the level of deformation exhibited in a material as a result of an applied force. The ratio of length change in a material to the original and unaffected length thus defines strain (Instruments, 2017) (Figure 3-3), and it may be positive or negative. A positive or tensile strain emerges as a result of elongation, whereas negative or compressive strain results from contraction.

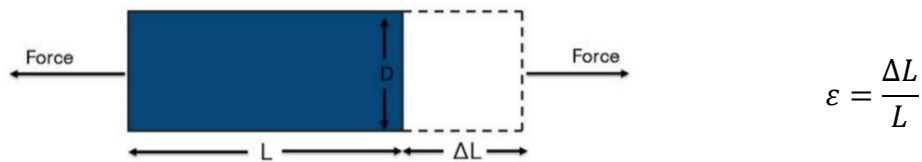


Figure 3-3: Strain (Instruments, 2017)

Chapter 3: Methodology

In the current test, BFLA-5-8 strain gauges were used, produced by the *Techni Measure Company*. This strain gauge is designed specifically for the measurement of composite materials. This model possesses a specially designed grid configuration to reduce the gauge's tightening effect on the test specimen. This series is recommended particularly for carbon, ceramic and composite materials, (Instruments, 2017).

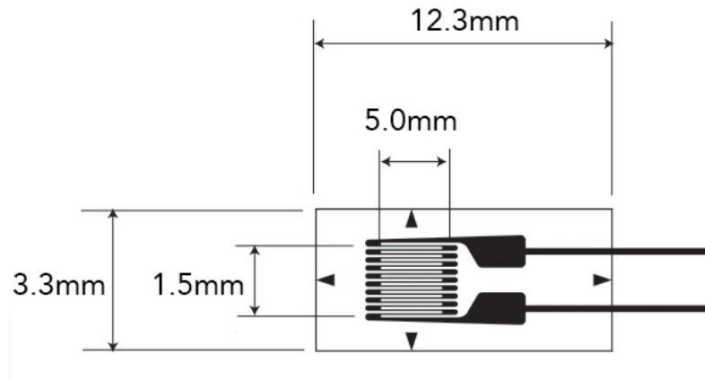


Figure 3-4: Strain gauge dimensions (Instruments, 2017)

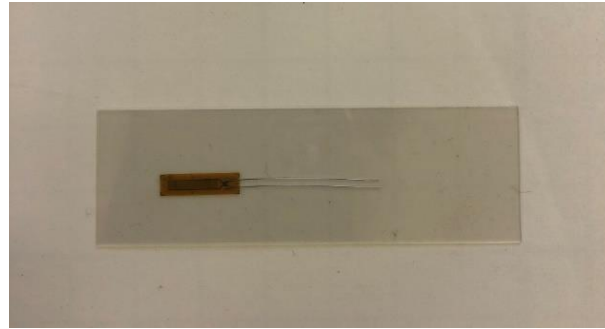


Figure 3-5: Strain gauge

Table 3-2: Strain gauge specification (Instruments, 2017)

Resistance	12 Ω
Applicable specimen	Composite material
Backing	Polyimide
Operational temperature (°C)	-20~ + 200°C
Element	Cu-Ni
Strain Limit	3%(30000 $\times$ 10 ⁻⁶ Strain)
Bonding adhesive	CN, NP-50B

To study bending active structures' behaviour, samples with various cross-sections and modulus of elasticity were chosen. Sample's material specifications were presented in Table 3-1. To study the stresses created during the experiments, six strain gauges were installed along the samples. Their positions on each sample were shown in Figure 3-6. The red points represent the strain gauges' position on the members with the spacing of 0.25% of the whole length between gauges. As the gauges were located on the samples' surface, the axial strain created could be measured. This experiment further shows the symmetry in the gauges' positions to maximize the experiments' accuracy and avoid any possible errors.

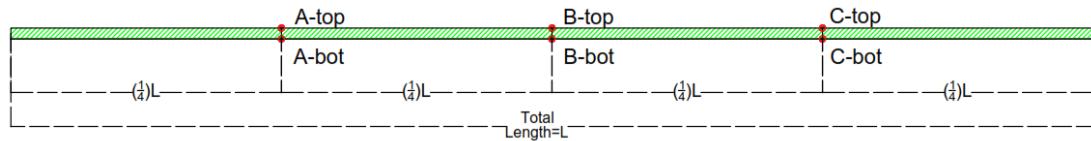


Figure 3-6: The strain gauges positions on samples

3.3.1.1.2. Pump

As the required force applied on samples in the tests is under 1000 N, a 4.5-tonne hydraulic hand pump (which was the closest available to the intended purpose) was selected for point loading test.



Figure 3-7: Hydraulic Hand Pump with Single Acting Hollow Ram Cylinder

3.3.1.1.3. Data logger

Collecting data provided by experiments requires a data collection program and a data logger. In this research, the program utilised was *Servocon*, and the programming code was made in *LabVIEW* provided by the National Instruments Company. The *SCXI-1000* data logger is a low-noise, rugged chassis that powers *SCXI* models. The data logger handles the routing between *SCXI* models and other models in terms of the trigger, timing and signal routing. The strain gauges were glued to the samples and connected to the computer by the data logger.



Figure 3-8: Data Logger

3.3.1.1.4. Protected shield

Lab environments present different sources of hazards. Apart from PPE, which is mandatory to use in the laboratory area, a safety shield was located by the operator to act as a barrier between them and the sample to prevent any hazard during the testing procedure. As it is possible, samples used in the test might fracture or break away during loading tests.

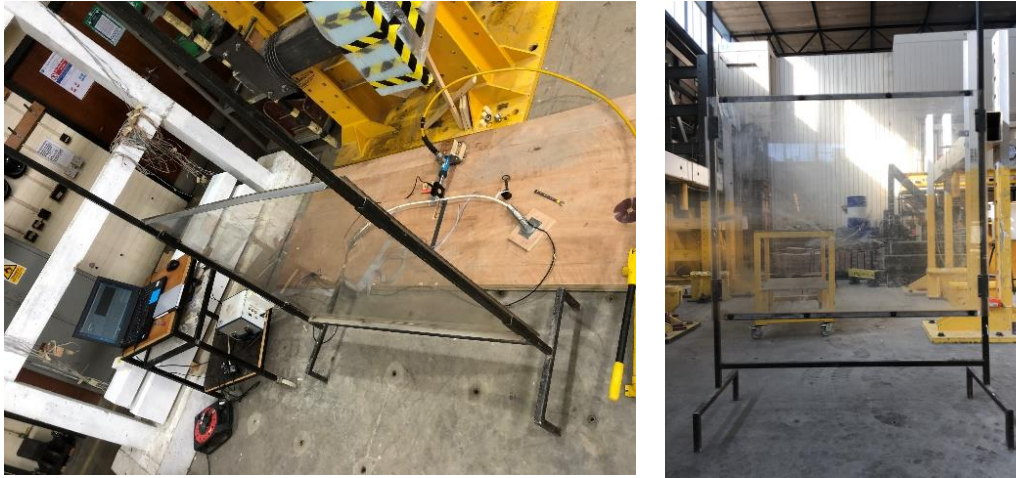


Figure 3-9: Protector Shield

3.3.1.2. Boundary condition

Side joints

In order to stabilize the two ends of the rod in place, two base jaws were used. Two sockets that acted as fixtures were carefully constructed and connected to each jaw to minimize the invading forces on each extreme, as presented in Figure 3-10. The sockets were made in various sizes and diameters so that the test could be applied on rods with different thickness levels. To continue the test with flat strips, two three centimetre depth grooves were delicately cut in jaws in diameter. In this way, the rod could be replaced with a flat strip, and the same procedure could be conducted one after another.



Figure 3-10: Side joint and sockets

3.3.1.3. Machinery

3.3.1.3.1. Testing Rig

A wooden deck used as a platform for running the point loading tests. The deck consists of two pieces of whole MDF sheets ($1.22\text{ m} \times 2.44\text{ m}$) which tightly screwed to each other and subsequently bolted to the ground (Wolfson Building, Department of Civil Engineering). Doing this helped to control any vibration and movements and thus ensure safety during the tests. The platform's width was chosen with the aim of it being large enough for two different samples rods (1 and 2 meters), possessing different lengths to be tested on. The aforementioned pump was fixed on the top centre of the MDF sheet, and behind it, a wooden block was placed to secure the pump. Here, a third sheet ($0.8\text{ m} \times 2.44\text{ m}$) was placed under the side joints to bring the sample to the same height level of the pump leg to help applying load perpendicularly to the centre of the sample.

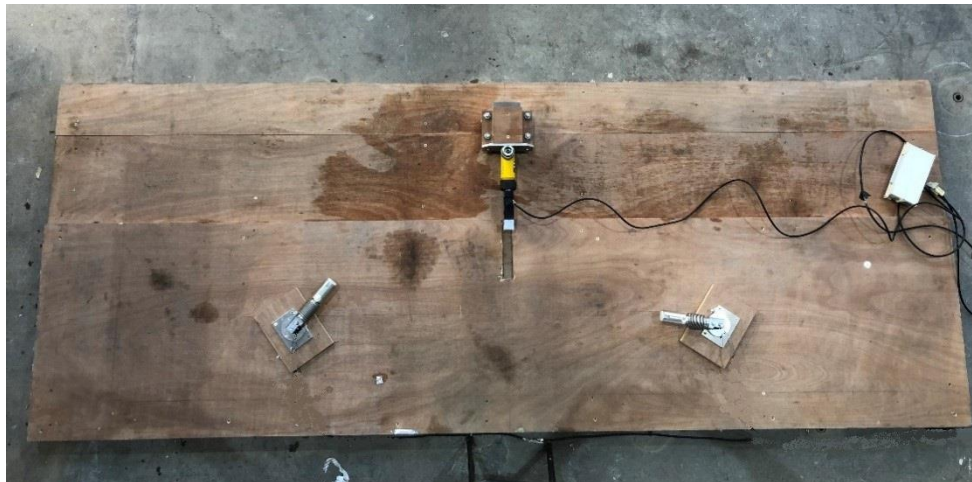


Figure 3-11: Point loading wooden rig

3.3.1.3.2. Ovens

Two different environmental chambers were used to apply temperature loading to the samples. The first environmental chamber shown in Figure 3-12 is located in the *Marmont Lab* in the *Architecture and Built Environment department of the University of Nottingham*. The *WIR36-5S* chamber is manufactured by *Design Environmental Ltd*

(no longer trading). The internal dimensions of the chamber were 4 m × 3 m × 2.8 m (l×w×h) with the temperature range was between -5 and 50°C.



Figure 3-12: WIR36-5S Environmental Chamber



Figure 3-13: ALPMA 1550-40M Environmental Chamber

The second chamber (Figure 3-13), located in the *L2 Engineering Laboratory of the University of Nottingham*. The ALPMA 1550-40M chamber, is manufactured by *Design Environmental Ltd*. The chamber's temperature range is between -50 and 250°C. The primary purpose of using this chamber was to determine the effects of fatigue on the considered samples caused by cyclic temperature loading. The chamber possesses programming capabilities allowed the simulation of day and night temperature cycles and performing the experiment in temperatures below -5 and above 50°C (up to 250°C) in as many different periods as possible.

3.3.1.3.3. Tensile testing

During the development of new processes or materials, tensile properties were frequently measured. This allowed for the comparison of the different processes and materials. Tensile properties are further utilised to predict material behaviour under loading forms other than uniaxial tension (Khayal, 2019). Tensile testing was thus

carried out during the present research to compute tensile stress and further determine the modulus of elasticity evident in the samples which had undergone various temperature loadings.

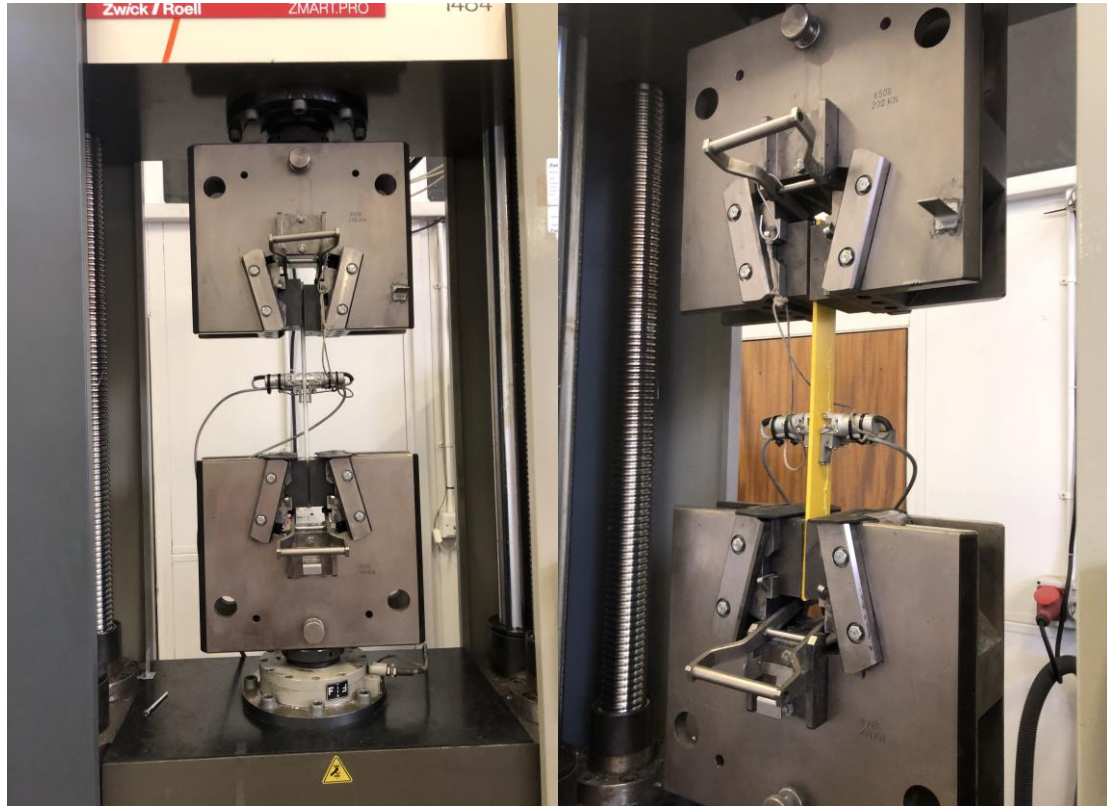


Figure 3-14: Universal test machine used to test tensile specimens

3.3.1.4. Tests

3.3.1.4.1. Sample Preparation

To perform the test, samples with lengths of 1 m and 2 m were chosen. The first step of the sample preparation was to determine the right location for stress measurement. Locating gauges in flat samples proved easier to work compared to round shape cross-sectional samples. A single plane digital height gauge was used to find the exact upper and lower web location (located 180 degrees from each other) on the circle cross-section samples. As the diameter of the sample is known, the height of the scribe was set to the half measurements of the sample's diameter. After fixing the

sample on a flat surface, a line was marked by the scribe all over the sample (on one side). By moving the gauge to the opposite side of the sample, another line was plotted. As the sample was completely fixed on its position the two lines were located 180 degrees to one each other. As the upper and lower web's location were defined the strain gauges were attached to the desire places. As the lines plotted by the scribe were not visible in the pictures captured by the camera, they were highlighted by a marker to make the plotted lines visible as presented in Figure 3-16.



Figure 3-15: Single plane digital height gauge



Figure 3-16: Strain gauge position marking

Surface preparation steps before strain gauge installation

To measure the strain created in the samples, *BFLA-50-8* strain gauges were used. Before installing the strain gauges, samples' surfaces were required to be prepared. Figure 3-17 presented the facilities for strain gauge installation. Firstly, the surface of the specimen was roughened with the 3200 sandpaper. This was done to create more friction on the surface to stabilise the strain gauge. Then, *M-LINE GC-6 ISOPROPYL ALCOHOL*, *MCA-1 M- PREEP CONDITIONER A*, and *Neutralizer 5A (MN5A-1 M- PREP NEUTRALIAER 5A)* were employed to clean samples' surfaces, respectively. After that, the strain gauges were glued to the specimens using 200 CATALYST and

M-BOND 200 ADHESIVE. Solder terminals were installed between the connecting cables (data logger) and the strain gauge to prevent any disconnection during the tests as shown in Figure 3-18 (Techni Measure, 2017).

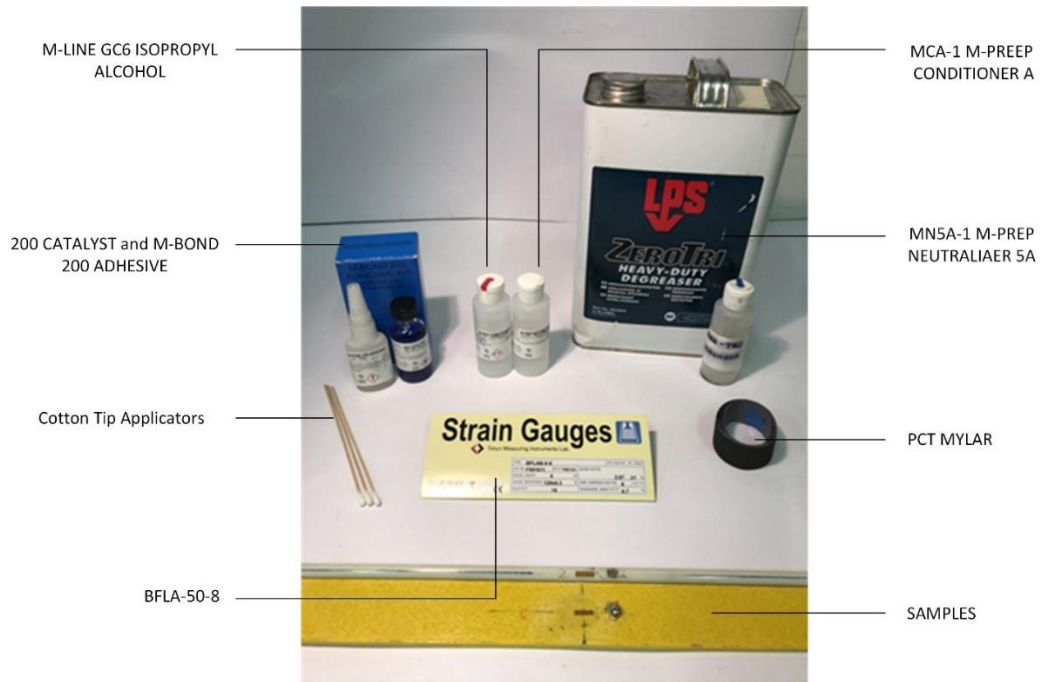


Figure 3-17: Strain gauge installation facilities

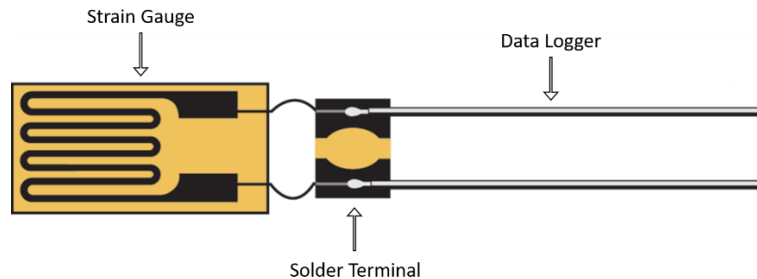


Figure 3-18: Connection of a strain gauge and data logger using solder terminal

Tensile testing

After subjection the samples to temperature loading, 1 m samples were cut to create samples with smaller length of 0.4 m for different tests. Three pieces were utilised for each occasion to determine the average of the estimation.

3.3.1.4.2. Test procedure

To understand the structural behaviour of bending active samples under bending and loading, various steps were taken. While the samples were in a rest position, the data capture system started. Then, the GFRP samples were bent and located in the sockets on jaws. A point load was gradually applied to the middle of the sample. Load application was managed in several steps until the sample reached 50 mm displacement (the top of the crown) from its original position. An unloading step was gradually engaged to reach the point whereby the sample was completely unloaded. The sample was removed from the jaws and returned to the original rest position in the next stage. This was the end of point loading experiment.

In this research, the conducted experiments are divided into two general categories, as follows:

Category 1: Experiments investigating the behaviour of Bending Active structures due to bending and external loading.

- i. Bending tests: Specimens were bent by moving their ends towards each other to create bending active.
- ii. Experiments including Point Loading: Point load applied to the arc's crown (bent elements), and loading increased and decreased incrementally.

Category 2: Experiments investigating the behaviour of Bending Active structures due to temperature changes.

- i. Tensile tests after applying temperature changes: In these tests, samples were pre-treated by temperature loading, then changes in the strength parameters of materials such as the modulus of elasticity and yield stress were studied.
- ii. Experiments including point load after temperature changes: Experiments after applying temperature load to the materials, the models were initially bent, then the point load applied to the arc's crown.

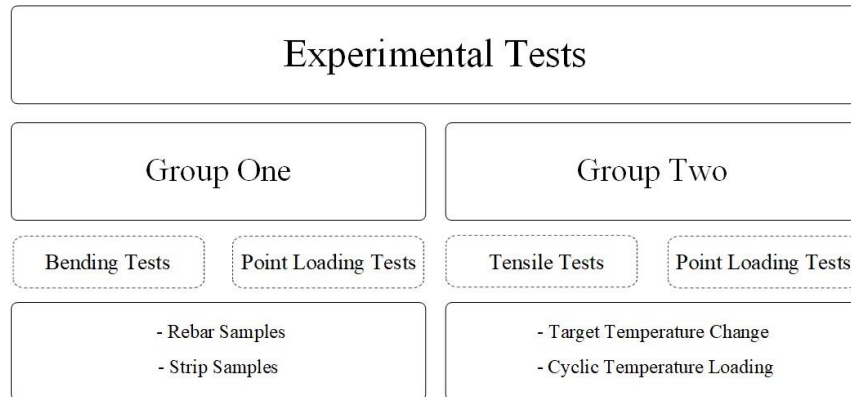


Figure 3-19: Tests procedure chart

3.3.1.4.2.1. Group one Experiments

To investigate the effect of bending, models were subjected to initial bending by displacing the two ends in a horizontal direction towards each other using hands and placing in the jaws. The axial strain was obtained at the dedicated strain gauges' locations.

In the point loading experiment, at first, the initial bending was applied to the models, then a pressure jack was used to apply point loading to the arc's crown. Loading was increased and decreased incrementally, and the axial strain values created in the gauges was measured at each step.

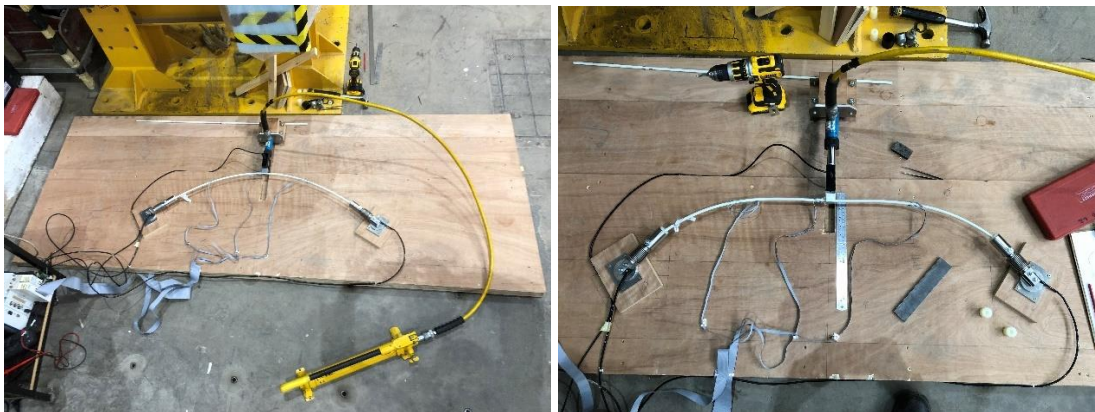


Figure 3-20: Point loading

3.3.1.4.2.2. Group two Experiments

In these groups of experiments, members were subjected to temperature loading, and changes were applied in two different methods prior to point loading. In the first

group, the temperature change was applied to the samples, from preliminary to secondary temperature (target temperature loading). To investigate the effect of different temperature on material's properties, samples were subjected to the temperature change from the primary temperature of 24°C to secondary temperatures of -5°C, 0°C, 10°C, 20°C, 30°C, 40°C, and 50°C during 16 hours in separated tests. The chamber was set to reach the secondary temperature over 60 minutes from 24°C and then returned to the original state gradually over last 60 minutes.

In the second group, the cyclic temperature change was applied to the samples to investigate daily temperature changes on sample's behaviour. These patterns were picked from various cities and countries. For instance, the average temperature in Milan, Italy, follows pattern type 2 (Figure 3-21). The applied cycles were the same for both patterns and are equal to 48 cycles. In pattern type 1, the temperature was reduced to -5°C and remained at this temperature for 20 minutes. The temperature was then increased to 50°C (over period of 40 minutes) and kept at the constant temperature for 20 minutes. Temperature returned to -5°C over period of 40 minutes. This process repeated for 48 times to represent 48 cycles. In pattern type 2, during the first 20 minutes, the temperature was fixed at 5°C and then within next 40 minutes, the temperature reached 30°C and maintained constant for 20 minutes. Finally, the temperature was reverted to 5°C within 40 minutes and stayed constant for 20 minutes, as illustrated in Figure 3-21.

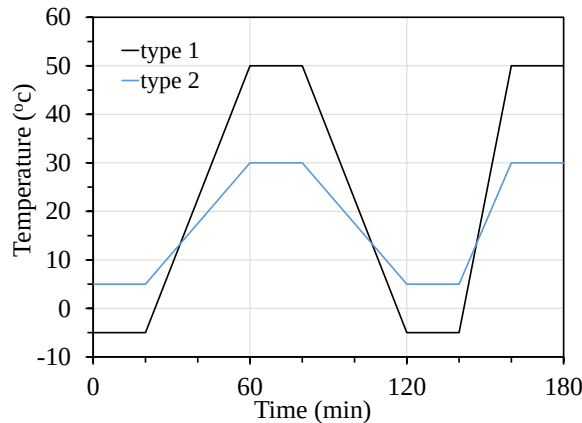


Figure 3-21: Temperature cyclic change procedure

In order to investigate materials behaviour after the applied temperature changes, the relevant experiments were performed in the following two cases.

For tensile testing, 1 m samples subjected to temperature changes cut into 0.4 m long pieces. Subsequently, the samples were examined with tensile testing to measure the modulus of elasticity and yield stress parameters.



Figure 3-22: Tensile test samples

After applying temperature changes to the models, samples with a length of 1 m, each support moved 50 mm towards each other generating the secondary span of 0.9 m. Then samples were subjected to the initial bending and point loading in several steps. Table 3-3 presents the list of tests performed on samples in each group.

Table 3-3: Bending and loading tests

Test		Test No.
Group 1	Bending	1-1 to 1-11
	Point load	2-1 to 2-12
Group 2	Tensile	3-1 to 3-18
	Point load	4-1 to 4-24

To obtain mean value for each test the empirical rule (the 68–95–99.7 rule) was used to calculate around 95% of scores within four standard deviations of the mean for three repeated tests.

3.3.2. Wind

Wind tunnel testing is one of the most valuable approaches to studying the wind flow around structures. In most cases, to perform wind tunnel testing, models are simulated on a small scale due to laboratory limitations. Simulation requirements, such as flow and structure conditions, should be considered when producing laboratory results to be related to the full-scale model. The study aims to investigate the effect of wind flow on pressure distribution of bending active structures.

The use of laboratory methods is feasible in two ways. Firstly, by full dimensions testing and secondly by full-scaled testing. Within the context of the full scaled laboratory method, the original model is being tested. Apart from its analytical approach, it is a method often introduced as the main reference for a more accurate estimation of wind tunnel analysis and numerical simulations. In addition, the laboratory method plays an important role in validation. The second method, known as scaled, the objective is to estimate and evaluate the effect of wind flow on structures.

In contrast to the laboratory method, the regulatory method uses valid standards and regulations which is core principle for the wind tunnel tests to be performed on a model with simple structures. However, limitations such as; structural geometry, individual structure, non-consideration of dynamic properties and the use of it as a complete reference is inaccurate.

Due to the constant evolution of modern technology, numerical simulation and the use of computational fluid dynamics methods have been proposed as complementary methods and are suggested as alternative methods for studying the effect of wind on structures. It is important to note that regarding the numerical simulation method, to ensure success from the numerical simulation method, the use of laboratory models is somewhat crucial (Vesmawala et al, 2009). Despite the progress being made, to date,

there has been no definite process regarding the design of bending active structures encountering wind currents. This deficiency in research has formed uncertainties surrounding the wind effect estimation due to the lack of specific information on flexible light structures design in standards and regulations. Therefore, the investigations regarding the wind effect is of great importance (Taranath, 2009).

In wind tunnel laboratory tests, there are three basic tests that are used to study the flow behaviour around the structure. These include the Rigid Pressure model (RP), High-frequency model and Aeroelastic model. Within the rigid pressure model method, the pressure is measured at the local points marked on the structure, which is used to estimate the structure's structural cladding elements. Using this method, the determination of the average total force applied to the structure is also done using the mean values of pressure. In the high-frequency method, forces are used directly to determine the dynamic response to the structure. In other words, the structure is rigidly modelled, and the values of force and bending moment were calculated. Finally, in the aeroelastic model method, due to the structure's behaviour and deformation against wind current all forces, displacements and accelerations applied to the structure are measured directly. Furthermore, in addition to structural geometry requirements, it is necessary to properly observe the principles of dynamic similarity (Tamura, 2013).

As a method, studying pressure distribution on structures is regarded as an effective method for estimating wind force. Pressure distribution on the structures depends on several parameters such as; the surrounding environment, structure's dimensions and location. One of the wind tunnel testing methods measures the pressure distribution on the surface of the structure. This method is used to measure the pressure and the suction on the structures to determine the mean wind force on the structures using the measured mean pressure.

3.3.2.1. Wind Tunnel basics

Several essential similarity requirements should be followed when undertaking the wind tunnel experiments:

- The same geometric scale must be used (Some deviations are permitted).
- The blockage ratio should be checked in the geometric scale.
- The same statistics of mean and fluctuation wind must be used in terms of dimensionless space and time. Similarity should be fulfilled along with wind turbulence and the mean wind profile. The scaling requirement is essential given that the windward face pressures are strongly dependent on the incident velocity profile; pressures on alternative faces depend on the incident turbulence's integral length and intensity parameters.
- Reduced velocity (U/f_0B) should be same in both scaled model and full scale model. Following from other requirements, scaling the frequency ratio (ratio of the model to full scale frequency λ_f) is related to the geometric scaling ratio (λ_B) and the velocity ratio (λ_U) (Snabjorsson, 2002).

$$\left(\frac{f_s L}{U}\right)_m = \left(\frac{f_s L}{U}\right)_p \Rightarrow \left(\frac{L_m}{L_p}\right)\left(\frac{L_{sm}}{L_{sp}}\right) = \left(\frac{U_m}{U_p}\right) \Rightarrow \lambda_B \lambda_f = \lambda \quad \text{Equation 3-1}$$

- Similar Jensen numbers (h/z_0) should be maintained.
- The density ratio (ρ_s/ρ) should remain the same in the model and prototype. ρ is the air density and ρ_s is the bulk density of the building.
- The *Reynolds* number (Re) similarity in model and prototype is imperative. However, frequently this requirement is not possible. The Reynolds number similarity ensures that viscous effects will be accurately modelled (ASCE, 2012):

$$\left(\frac{\rho UL}{\mu}\right)_m = \left(\frac{\rho UL}{\mu}\right)_p \quad \text{Equation 3-2}$$

Here, μ it represents the viscosity of air. In most structures, a failure to satisfy this relationship is not a concern. This is because most structures possess sharp edges, which serve to dictate the patterns of airflow. In curved surfaces (e.g., circular cross-sections), a lack of the Reynolds number similarity may result in significant differences between the model and full-scale response. Thus, any tests on structures that are Reynolds number

sensitive should be adapted for such differences using available full-scale measurements or relevant test data as a basis.

- When evaluating aeroelastic models, an observation of the scale of the models applied structural characteristics should be performed.

Model Scaling

The geometry scale ratio employed in wind tunnel test was 1:10, in accordance with the similarity requirements. The region's roughness and velocity profile values were established with the same geometrical scale ratio described in the upcoming sections. Four base speeds were applied to the model to compare the performance at different speeds. For 600 seconds of testing in the actual model, the laboratory model's data extraction time was estimated to be 200 seconds.

Table 3-4 listed the sampling time ratio, as well as other scaling parameters. The *Reynolds* number of the laboratory model was smaller than the actual model, which was expected. According to a study by Quan et al. 2014, a *Reynolds* number greater than $2.48e^5$ for a height to span ratio of 0.33 had no significant effect on pressure coefficient distribution (Quan, 2014). Due to the purpose of investigating the pressure distribution on bending active structures, the wind tunnel experiment method was similar to the rigid laboratory method. However, in this study, the laboratory models were executed with the same material and formation process as the actual bending active structures. Thus, the ratio of model density to the actual model is correctly allocated.

Table 3-4: Scaling Parameters

Variables	Values
Geometric scale ratio (L_m/L_P)	1:10
U_m (m/s)	4 m/s, 6 m/s, 8 m/s, 10 m/s
U_P (m/s)	13.33 m/s, 20 m/s, 26.67 m/s , 33.33 m/s
Velocity ratio (U_m/U_P)	3:10
Time ratio (t_m/t_P)	33:100
Time for prototype (sec)	600
Sampling time model (sec)	200

3.3.2.2. Wind Tunnel Facility

The *University of Nottingham's L4 Mechanical, Materials & Manufacturing Engineering Wind Tunnel* is a low velocity atmospheric boundary layer wind tunnel. This wind tunnel was built to perform aerodynamic studies on structural models. The atmospheric boundary layer was replicated with surface roughness elements and spires, allowing for natural wind simulations to be performed. The holistic illustration of the *L4 Wind Tunnel* is given in Figure 3-23. The wind tunnel has a test section of 14 m in length, with a cross-sectional area of 2.4 m in width, and the height is 1.80 m (after the contraction part and extends up to 1.90 metres after the turntable). The wind tunnel is combined with a turntable of 2.0 m diameter, located 12.5 m away from the beginning of the test section, allowing multidirectional wind studies (Sofotasiou, 2017).

The wind tunnel further possesses an axial fan that enables the generation of velocity speeds up to 11 ms^{-1} when it is empty. Flow homogeneity was achieved via installing a series of equidistant blades (0.45 m) at the upper and lower contraction corners and at the end corner of the diffuser. Additionally, the wind tunnel was combined with a 0.45 m thick honeycomb and a fibre mesh series. These factors operate as flow straighteners whilst simultaneously preventing large particles appearance in the test section (Sofotasiou, 2017).

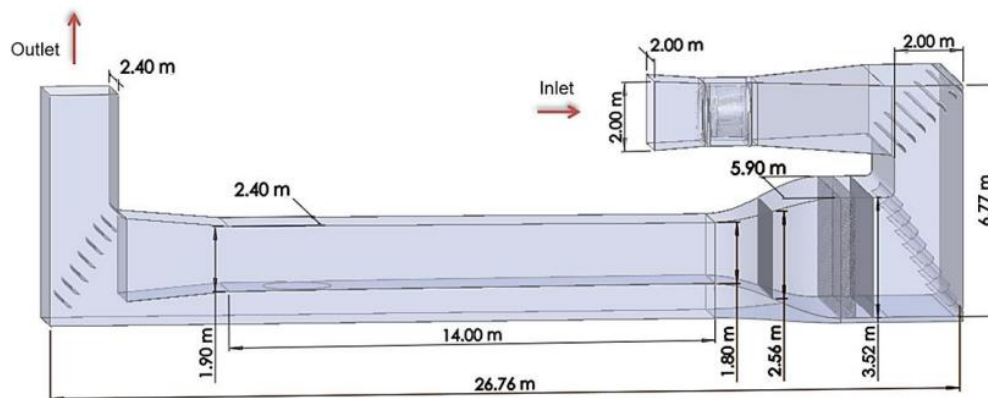


Figure 3-23: Illustration of the total ABL of “L4” wind tunnel facility (Sofotasiou, 2017)

3.3.2.3. Boundary Layer Simulation

The atmospheric boundary layer (ABL) constitutes the lowest part of the atmosphere, with the effect of temperature, surface roughness and other properties transmitted via turbulence in this layer. The depth of this boundary layer varies depending on the atmospheric condition (Burton, 2001). Spires, a barrier wall, grids and roughness elements all help in the performance of boundary layer simulations and allow for the facilitation of boundary layer growth and the mean velocity profile (Burton, 2001). The best simulation procedure depends on the characteristics of an individual wind tunnel and the objectives for ABL testing (Gulsten, 2010).

The spires' primary function is to generate vertically oriented eddies through the abrupt flow separation around the edge of the spires (Gulsten, 2010). A barrier is placed with a separation that is one third of the boundary layer height from the tunnel contraction in the first position. Turbulence is directly affected by the barrier's height, as higher barriers result in greater observed turbulence. The distance between the starting point of the roughness elements and the end of the spires is not found to be a critical downwind of the spires (Hobson, 2015). An arrangement of roughness elements mimicking the earth's surface can be used. In such cases, air flows across the roughness elements forming turbulent eddies. Eddies are analogous to the wind flowing over surface structures (e.g., dunes, vegetation and waves). Turbulence and a velocity gradient are induced in the flow due to this (Hobson, 2015).

In the current study, the boundary layer simulation configurations include a fence and five spires with cubic roughness blocks covering the floor of the test section from the spires (the length of these are 9.67 m downwind of the structure), as depicted in Figure 3-25. The configuration of different devices results in the height of roughness of 0.01 m (details of the component arrangements in the wind tunnel are depicted in Appendix B).

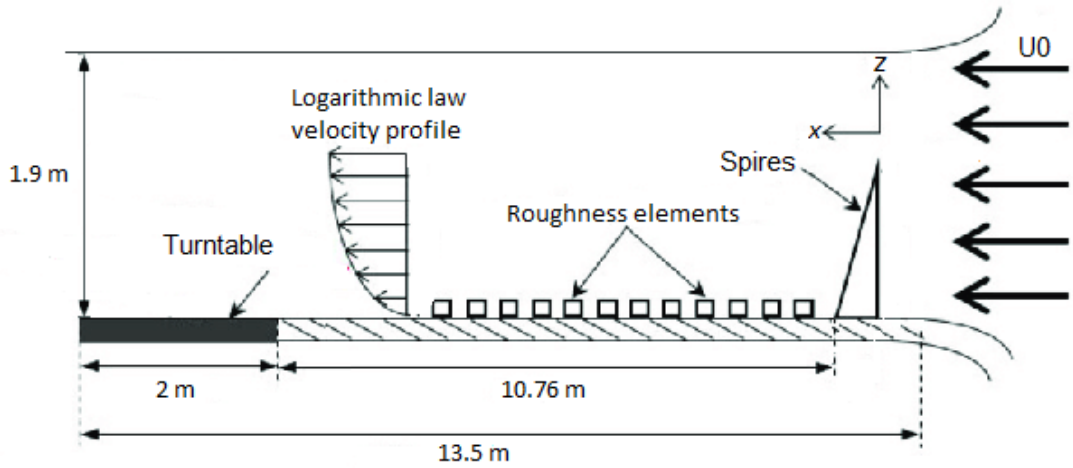


Figure 3-24: Schematic diagram of boundary layer wind tunnel



Figure 3-25: a) Spires and roughness elements b) Roughness elements and the structural model placed on the turntable

A combination of surface roughness and spires were utilised to create an approach flow profile of wind, representing the lower section of a boundary layer that is both neutral and atmospheric. The mean streamwise velocity of the approaching flow obeys the logarithmic law (Tominaga and Blocken, 2015):

$$U(z) = \left(\frac{u^*}{K} \right) \ln \left(\frac{z}{z_0} \right) \quad \text{Equation 3-3}$$

Where, in this case, $U(z)$ represents the mean streamwise velocity at height z , K represents the von Kármán constant which is equal to 0.4, and z_0 is equal to the

aerodynamic surface roughness length (that is, the height where $U(z_0) = 0$). The mean friction velocity, u^* , is defined as $(\tau_0/\rho)^{1/2}$ representing the mean surface shear stress and ρ representing the mass density of air. The main parameters, in this case, are the wind velocity and the model scale, which are dependent on the *Reynolds* number. Table 2 depicts the conditions evident in this experiment.

Table 3-5: Parameters of the Test

Sampling time	200 sec
Wind velocity (U_0)	4 m/s, 6 m/s, 8 m/s, 10 m/s
Friction velocity	0.083 m/s
Reynolds number	$2.35 \times 10^5 - 5.86 \times 10^5$

The mean flow evident in the full depth boundary layer simulation was analysed once the evaluation of the empty tunnel was completed. The distribution of velocity along the central line is depicted in Figure 3-26 (a). Similar trends in the velocity profiles were seen and provided by the equation used above; Figure 3-26 (b) showing the turbulence intensity distribution at the same locations.

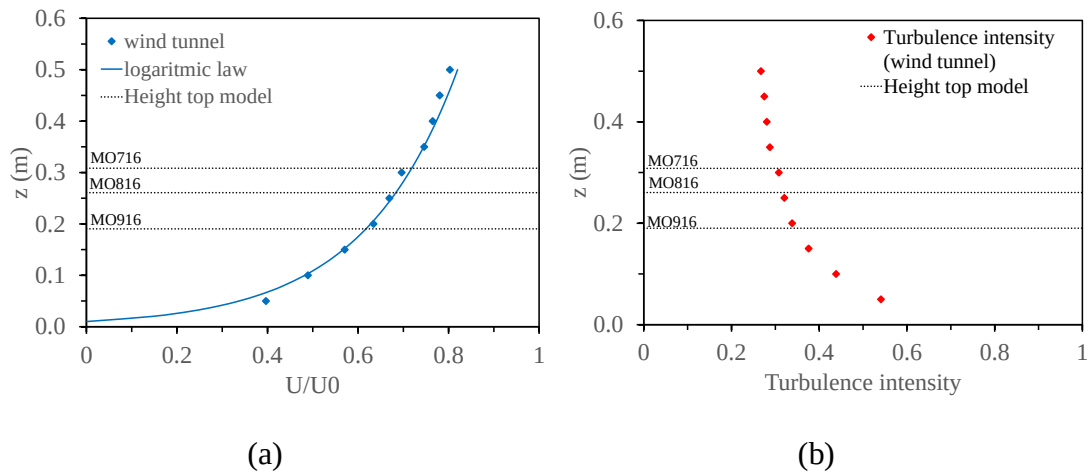


Figure 3-26 a) Mean velocity profile experimental values and logarithmic law fit b) Turbulence intensity profile

The reference speed and pressure were measured at the height of the structure. The measured values of the reference velocity were used to calculate the pressure

coefficient. The airflow characteristics during the wind tunnel tests were presented in Table 3-6.

Table 3-6: Characteristics of airflow during measurement in the wind tunnel

Model number	Air Temperature ($^{\circ}C$)	Atmospheric Pressure (Pa)	Air Density (ρ) (kg / m^3)
MO916	25	100556	1.1845
MO816	29	100600	1.1687
MO716	29	100600	1.1687
MC916	28	100559	1.1726
MC816	29	100600	1.1687
MC716	28	100559	1.1726
MT816	29	100600	1.1687
MT716	28	100558	1.1726

3.3.2.4. Equipment

3.3.2.4.1. Pressure and Velocity Measurement System

Velocity was measured using a Pitot static tube connected to a traversing system to 2 degrees of freedom, allowing positioning of the Pitot tube in the vertical and longitudinal directions along the middle of the tunnel. In the current project, only the vertical degree of freedom was used. A jackscrew assembly was used to raise and lower the Pitot tube. Height was measured with a ruler, which is placed adjacent to the jackscrew nut. The jackscrew nut was then positioned at the lowest possible height, and the Pitot tube centreline height was measured from the floor of the wind tunnel.

The measurements of Pitot static tube velocity use a well-known manipulation of the Bernoulli equation (Hobson, 2015):

$$V_{measured} = \sqrt{\frac{2 \times (P_{stagnation} - P_{static})}{\rho_{fluid}}} \quad \text{Equation 3-4}$$

Static pressure and stagnation difference were measured by connecting the static tube to the manometer's high side, connecting the stagnation to the low side (Hobson, 2015). In the current test, a standard pitot static tube was used. This tube was positioned in alignment with airflow (Sofotasiou, 2017).

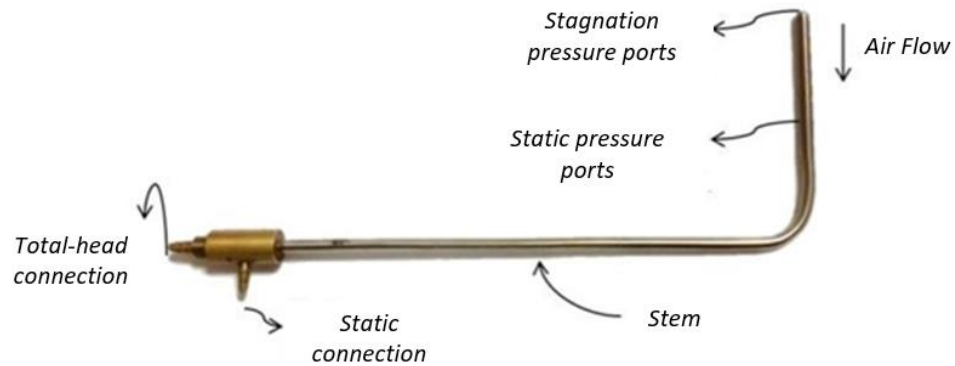


Figure 3-27: Standard pitot static tube (Sofotasiou, 2017)

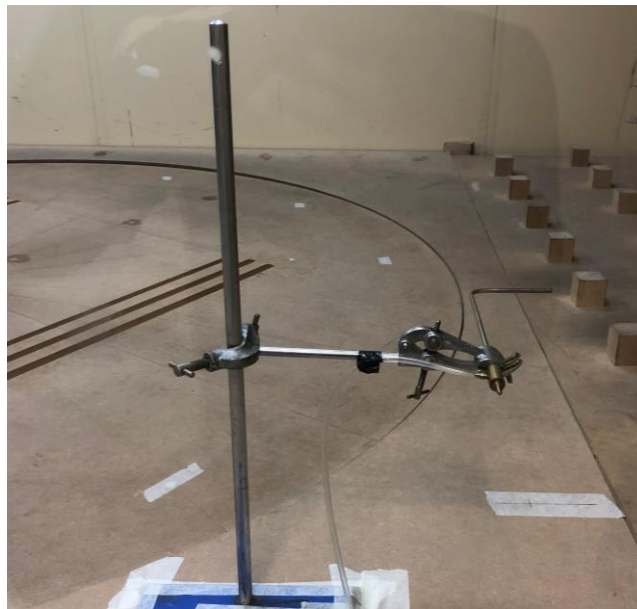


Figure 3-28: Pitot static tube used for the wind tunnel experiment

3.3.2.4.2. Wind Tunnel Pressure Measurements

Pressure taps locations, pressure tap diameter, transducer type, and wind angle were the four factors considered during the design stage and wind tunnel testing stage of this

research. Pressure tap location was selected to gain a more comprehensive understanding of how pressure is distributed on the model's surface (Goliber, 2009).

Pressure taps

Stainless steel pressure taps with diameter of 0.04 inches (1.016 mm) and lengths of 4 inches (101.6 mm) were used for the experimental test provided by *Evolution Measurement LTD*.

Transducer

Scanivalve's Miniature Pressure Scanner (MPS) was chosen as the pressure transducer. This scanner comprises 64 pressure taps and is considered one of the most accurate lab pressure transducers. The pressure data were sampled at 500 Hz (transducer capacity). Each transducer tap received a pressure input through a vinyl tube attached to a tap on the model. Subsequently, a corresponding was read as output and could be converted into the desired measurement unit. The vinyl tube has a diameter of 0.04 inches (1.016 mm) and a length of 1.3 m. These were kept constant for each tap and connect the pressure tap to the transducers (Goliber, 2009).

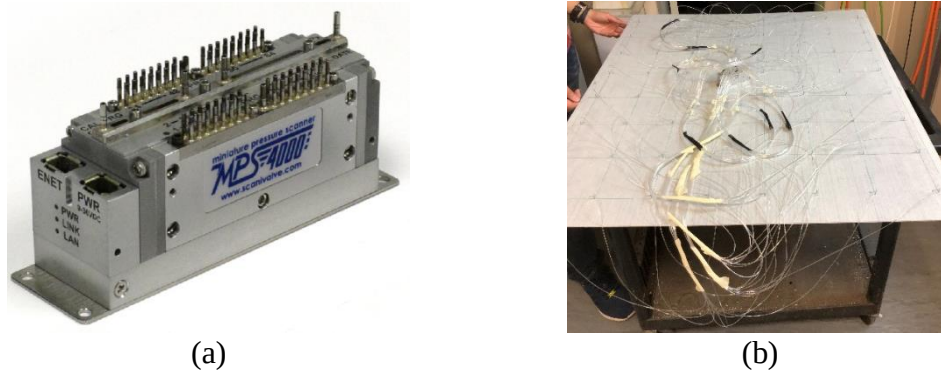


Figure 3-29 a) *Scanivalve's Miniature Pressure Scanner* with 64 pressure taps b) Pressure taps and vinyl tube were installed on the model

3.3.2.5. Experimental Model

3.3.2.5.1. Material and Dimensions

Three arched models, at a scale of 1:10 with different height to span (f/L) ratios were constructed using a GFRP plate. The plate dimensions were 1020 mm $\times$ 910 mm

with a thickness of 3.1 mm. The GFRP plate with characteristics 17 GPa Young's modulus, density of 1723.65 kg/m^3 and Poisson ratio of 0.28 were allocated for the tests.

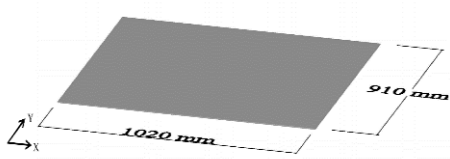


Figure 3-30: GFRP Plate's Dimensions

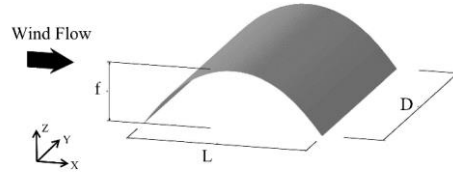


Figure 3-31: Models geometry

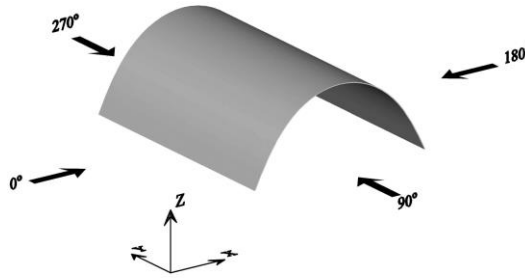


Figure 3-32: Wind Directions

Three grooves were created on the turning table plane to construct models with different span dimensions and height. These grooves were spaced apart, allowing for the creation of three different f/L ratios. Then, for the formation of the model, an initial curvature was applied to the sheet and depending on the desired f/L ratio placed in allocated grooves. Bending was applied in the longitudinal direction (in the length direction, 1020 mm) and the connection point of their support was considered as hinged support to allow models act naturally facing the flow. In Figure 3-33, examples of open models illustrated. During the testing and data collection, the front grooves in the sample were taped using masking and aluminium foil tape to prevent any extra flow distribution occurring during the test. To investigate the pressure distribution on closed models closure panels were placed on both side of models, although panels were laser cut in accurate size, to prevent infiltrate any airflow, intersection part between panels and model were also taped.

Each model tested between 0 and 360 degrees wind directions, with intervals of 15 degrees. The models were divided into open and closed groups. Each group had three models that each possessed individual rise span ratios (f/L) of 0.22, 0.33 and 0.44. In order to avoid blockage in wind tunnel experiments, it is important the blockage rate to be less than 10% (Balendra 1993). The wind tunnel section's maximum blocking rates for this test was 6.5% which fulfilled the requirements for the wind tunnel blocking rate. All relevant geometric parameters are given in Table 3-7.

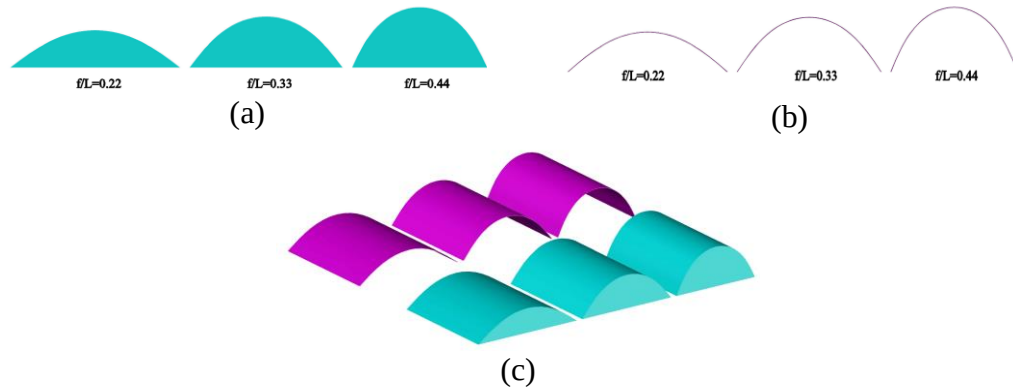


Figure 3-33 a) Closed models b) Open models c) Models perspective view

Table 3-7: Models Dimensions

Model	L (mm)	D (mm)	f (mm)	t (mm)	f/L
1	883.1	910	190.3	3.1	0.22
2	796.0	910	260.7	3.1	0.33
3	703.3	910	308.3	3.1	0.44



(a)

(b)

Figure 3-34: Experimental models a) opened model b) closed model

Closing the bending active models aimed to prevent wind flow under the model to investigate and compare the effects of wind flow on both open and closed models. In regular solid structures, when closing a structure, the panel's thickness was not indispensable when the aim was to close an open structure. Meanwhile, as the models were not solid in this study, the thickness and closure panel's position were critical. In closed span models, two very thin panels (2 mm thick) were placed on the models' sides. In this scenario models were not resting on the sides panels and the only purpose was to prevent the airflow through the models. Another closure method was also tested in the wind tunnel to investigate the effect of the side panels' thickness on pressure distribution. This time, two 20 mm thick laser cut wooden panels were located inside the model in a way which the outer side of the panels tangent with the edge of the models, and the models rested on side panels.



Before installation



After installation

Figure 3-35: Model with thick closure panels

3.3.2.5.2. Pressure Tap Locations

These tests measured local wind pressures from the model's external surface. $P_j - P_s$ (which P_j is the pressure at the measurement pressure tap j and P_s is the static pressure at the Pitot tube) were directly measured by the laboratory pressure transducer. The transducer acts as differential pressure, thus depicting the wind pressure acting at the particular pressure tap location j within the computer, as shown in Figure 3-36(a) (Nagai et al, 2011; Goliber, 2009). The pressure gauge valves were arranged at 8×8 , resulting in 64 pressure gauges installed on the structure's surface to cover the whole

surface of the samples. The taps and tubes were arranged reasonably to reduce the effect of them on the samples. Pressure tap locations were further explained in Appendix B.

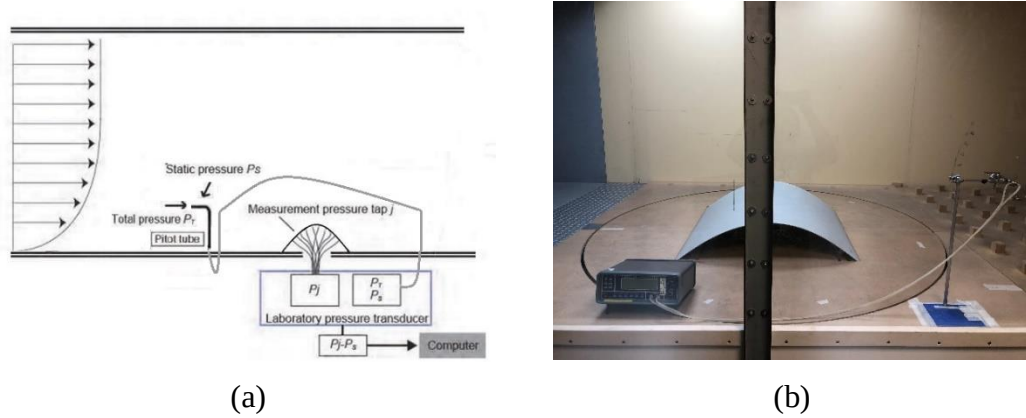


Figure 3-36: Measurement setup a) Schematic of the wind pressure acting at the particular pressure tap location j (Nagai et al, 2011), b) Wind tunnel

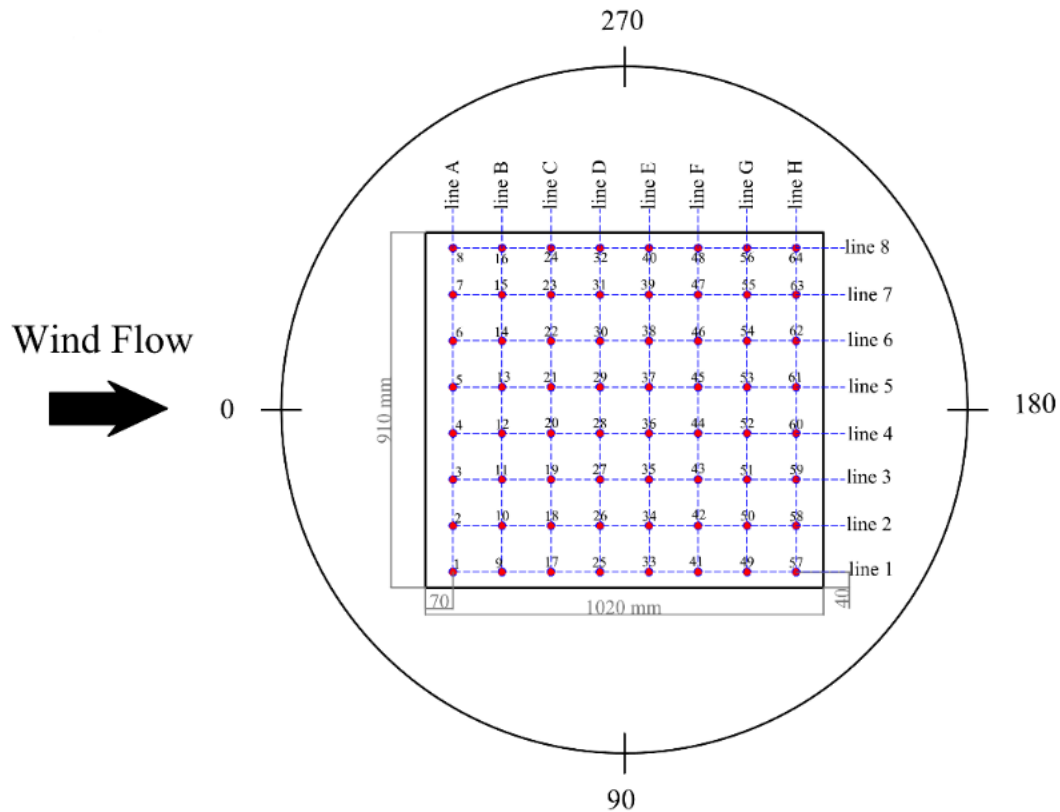


Figure 3-37: The pressure taps location on the model's surface



Figure 3-38: installed pressure taps

3.4. Numerical modelling

3.4.1. ABAQUS Modelling

Due to increased computation power and FEA software's ability to simulate complicated components, systems, and structures under a various situations, the utilisation of FEA tools in various engineering disciplines has become widespread. Perhaps one of the most popular software packages for FEA is ABAQUS. The reason for this is the possession of a number of functions in the ABAQUS suite that are useful for FEA. ABAQUS/CAE allows for the quick and efficient creation, editing, monitoring, diagnosis and visualisation of advanced analysis. Users favour this function as a result of the easy to use design. ABAQUS/Standard utilises technology to determine solutions for low speed and static dynamic events requiring highly accurate stress solutions. ABAQUS/Explicit is developed to simulate brief transient dynamic events (such as, short duration impact, ballistic impact, automotive crashworthiness, and drop testing of consumer electronics).

The report indicates modelling process employed in the ABAQUS software to be able to model the initial parts of bending active structures. Before proceeding with

modelling, it was essential to decide which system of units would be used. ABAQUS does not have a built-in system of units, and thus unit names or labels are not included when inputting data into ABAQUS. However, all inputted data must be specified in consistent units. Table 3-8 showed the common systems of consistent units. In the current projects, the SI (mm) system of units was employed (Abaqus-docs, 2017).

Table 3-8: Consistent Units (Abaqus-docs, 2017)

Quantity	SI	SI (mm)	US Unit (ft)	US Unit (inch)
Length	m	mm	ft	in
Force	N	N	Ibf	Ibf
Mass	Kg	tonne (10 ³ kg)	Slug	Ibf s ² /in
Stress	Pa (N/m ²)	MPa (N/mm ²)	Ibs/ft ²	psi (Ibf/in ²)
Density	Kg/m ³	tonne/mm ³	slug/ft ³	Ibf s ² /in ⁴

3.4.1.1. Material Model

To define a part or part region's properties, a section of unique material was created and assigned to the part. Sections mainly refer to the materials defined by the user (ABAQUS, 2014).

As ABAQUS does not have a material library, the user must enter the material's physical consistency into the software manually. Nonetheless, the software possesses an extensive library of common materials and is thus able to simulate many different material behaviour. Software's materials are not limited to the available behaviour, meaning that the user can define other specific or customised materials through the 'user-defined facility'. The material used in the current project was GFRP, which behaves here in the elasticity zone only. Thus, the available ABAQUS facilities were used to define the behaviour of GFRP, with this consisting of density, young's modulus and poison's ratio, as shown in Table 3-9.

Table 3-9: GFRP's properties

Description	Sections	
Property	Flat strip	Solid round rod
Density	1.9	1.9
Tensile modulus (GPa)	17	30
Poison's ratio	0.28	0.28

3.4.1.2. Mesh Convergence

To attain the suitable mesh size for the simulations, one of the bending models utilised as an example of mesh refinement by further analysing the rebar in ABAQUS. Four different mesh densities were utilised, presented in Figure 3-39. Table 3-10 indicated the number of elements utilised in each mesh. The stipulated model consists of rebar possessing a circular section ($R = 4 \text{ mm}$) with a length of 1 m . This sample was loaded to support point displacement, with each support being equal to 0.2 m .

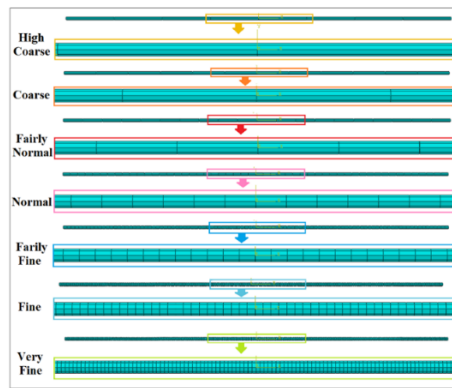


Figure 3-39: Meshing

The influence of mesh density was considered on two particular results from the model, the displacement of the top of the final curve and the maximum principal stress evident at the top of the final curve. Figure 3-40 showed the location where the comparison of the results takes place.

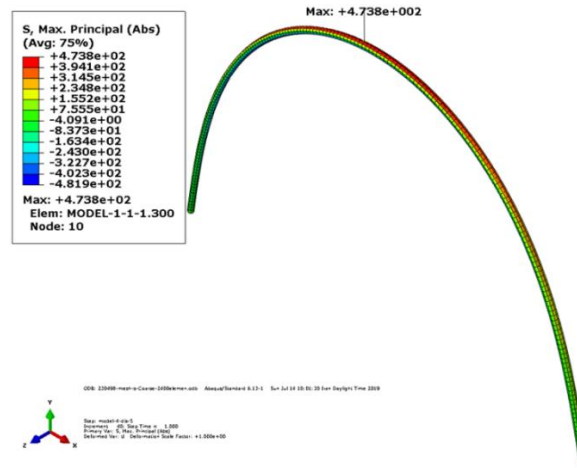


Figure 3-40: Locations where results are compared in the mesh refinement study (for example, 2400 element fine mesh has been shown)

A comparison of the results for each of the seven mesh densities presented in Table 3-10, as well as the required CPU time to run each simulation.

Table 3-10: Results of mesh refinement study

Mesh Quality	Length of the Element (mm)	Number of Elements	Displacement of the top node of the final curve (mm)	Stress at the top node of the final curve (MPa)	Total CPU time (sec)
High Coarse	200	97	334.2	3157.4	5.3
Coarse	100	144	343.7	2215.24	10.9
Fairly Normal	50	240	343.5	1439.54	11.6
Normal	20	624	343.4	731.38	55.1
Fairly Fine	10	1200	343.4	546.798	72.7
Fine	5	2400	343.4	473.76	112
Very Fine	2.5	4800	343.4	452.343	211

While all meshes predict similar results, the High Coarse mesh predicts less accurate displacements evident at the destination point. As far as the displacements were concerned, the coarse mesh converged and plotted in Figure 3-41.

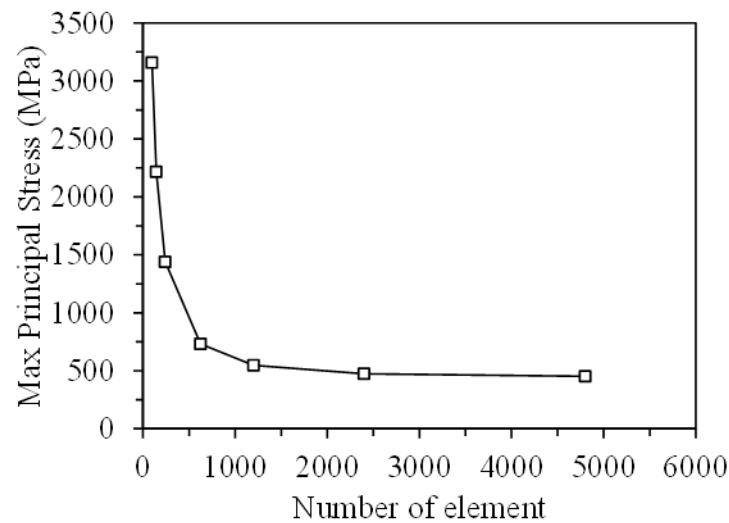


Figure 3-41: Convergence of results in mesh refinement study

As strain and stress were calculated from the displacement gradients, the peak stress, evident on the top point, converges much lower than the displacements. Therefore, a

significantly finer mesh was required to predict accurate stress placements, as opposed to that needed to calculate accurate displacements.

When the number of elements was increased from 2400 to 4800, the results changed by 4.5%, with CPU time doubling. The length of chosen elements was equal to 5 mm, which produced 2400 elements. Same mesh size was used to model the samples with the same geometry (cross-section and length). These factors were all considered when choosing the most appropriate mesh density in the current study.

3.4.2. ANSYS Modelling

ANSYS is the global leader in engineering simulations, offering a comprehensive software suite. Presently, computational fluid dynamics are equal with pure experiment and pure theory in terms of the analysis and problem solving of fluid dynamic problems (Yang, 2011).

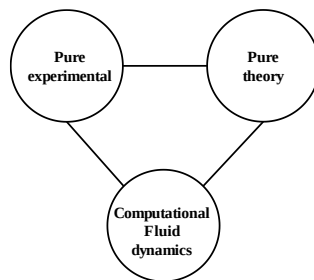


Figure 3-42: The “three dimensions” of fluid dynamics (Anderson, 1995)

In FSI, modelling encompasses the data exchange existent between the FEA and CFD solvers, which the ANSYS System Coupling Program governs as part of the program flow (Figure 3-43). The following section presents the modules in the ANSYS workbench for the analysis of FSI (Figure 3-44).

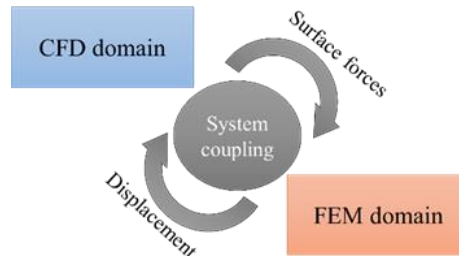


Figure 3-43: System coupling- flow chart

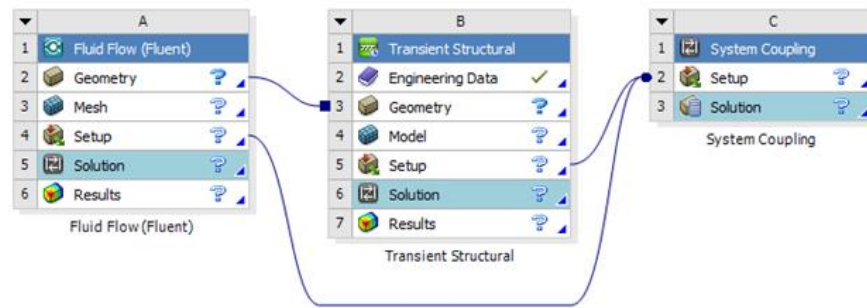


Figure 3-44: Fluid structure interaction (2-way) in ANSYS Workbench (ANSYS 2017)

3.4.2.1. Geometry

Geometry modelling using the ANSYS Workbench environment is characterized by high automation and the flexibility to customise models according to the type of application or analysis required. The ANSYS Design Modeler, which is feature based and parametric, can be utilised to create geometry from scratch or to prepare any existing CAD geometry for analysis. A key parameter in the modelling of airflow around a structure is selecting proper domains to eliminate the effects exhibited by domain walls on fluid flow. Moreover, the domain's size should be such that the blockage ratio is less than 3%. In the current research, the structure was first drawn in CAD before the geometry was imported in the Design Modeler draw the zones used in the meshing section (Figure 3-45).

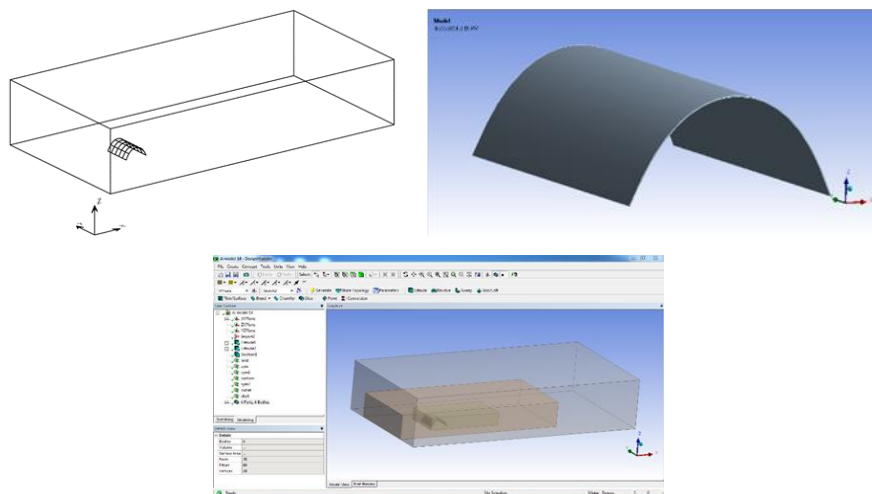


Figure 3-45: Drawn geometry

Rigid modelling

Selecting the exact computational domain regarding analysing wind flow around the structures as a consistent result has not been achieved. In numerical modelling, the specified dimensions were considered to be the same as the wind tunnel's dimensions, which was selected in the longitudinal direction (X) equal to 3.8 m, in the latitudinal direction (Y) equal to 2.4 m and in the altitudinal direction (Z) equal to 1.8 m. The structure was 2 m away from the flow input side. To control the mesh size around the structure, an internal area with dimensions of $1.2 \times 1.2 \times 0.4$ meters was defined inside the domain. The dimensions and specifications of the structure, internal and external domains were shown in Figure 3-46.

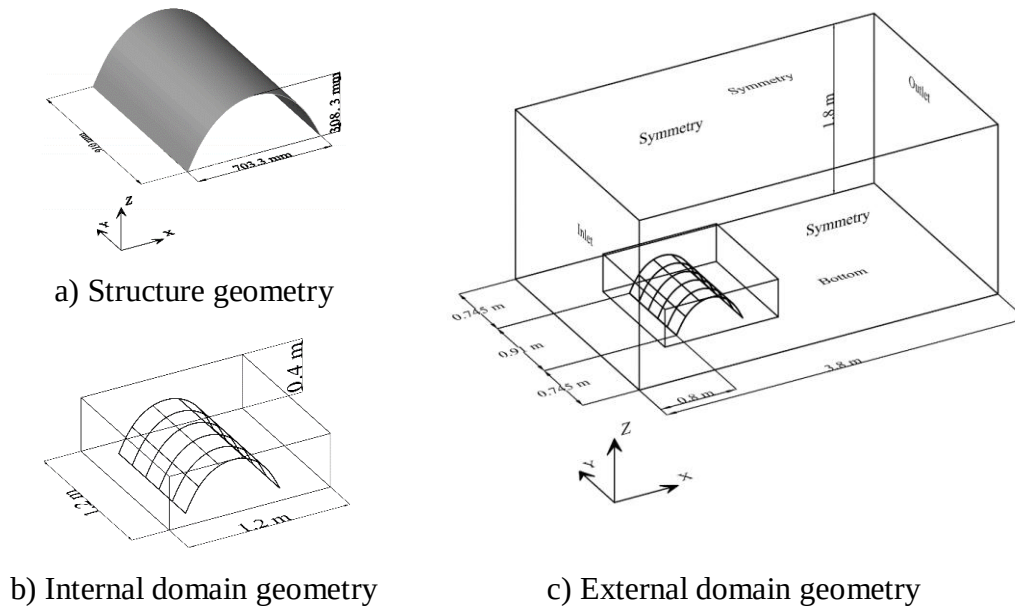


Figure 3-46: Structure, Internal and External domain geometry

Flexible modelling

The numerical calculation domain was created according to the part of the wind tunnel in which the velocity profile consisted of roughness elements. Numerical domain's dimensions and internal domain were considered to be the same as experimental laboratory which is same as rigid modelling as well. By consideration the

model symmetry, just half of the model has been model whit the aim of reducing analysis time.

3.4.2.2. Meshing

Numerical techniques are developed based on the Solve Spatial Discretization field. The implication of this is that only a few points are preferred as a basis for solving as a representative instead of a continuous space with extreme points. ANSYS Fluent is based on the finite volume method, typically divided into 2D and 3D categories. The type of grids in terms of the element or cell shapes are listed in Figure 3-47.

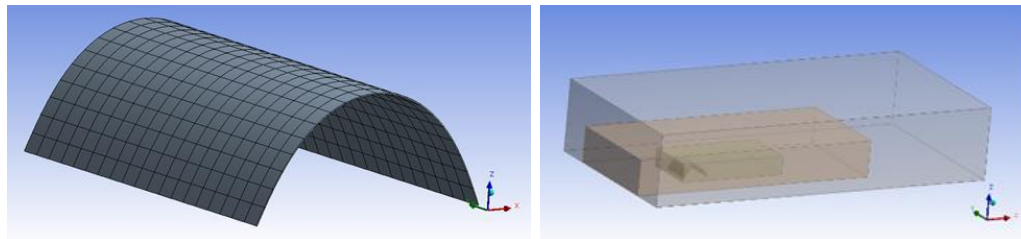


Figure 3-47: Drawn geometry

Rigid modelling

The mesh was created utilising hybrid mesh. This means all of the domains and structures were used as unstructured mesh and are only defined around the prism layer structure.

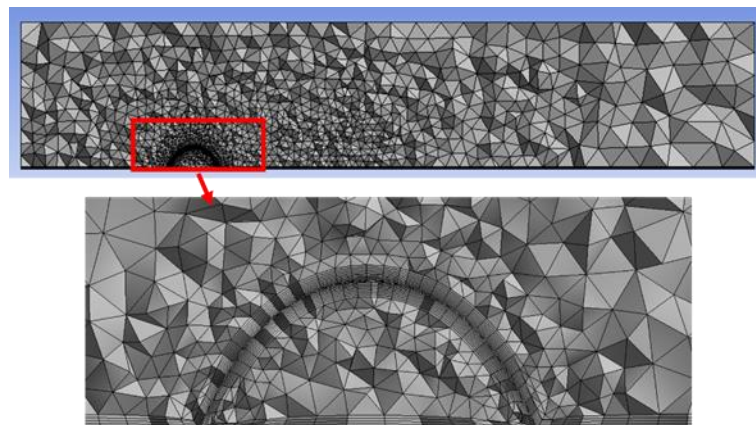


Figure 3-48: Meshing of the fluid domain

In this way, all domains were covered with tetrahedral mesh, although only around the structure, there were structured mesh with the initial height is 5 mm. The minimum

dimension on the structure surface was considered equal to 10 mm. Meshing arrangement were selected so that around the structure, there was a smaller element, and by increasing distance from the structure, the size of the element became larger (Figure 3-48). Consequently, total number of elements in the fluid part was 1746172.

Flexible modeling

Meshing elements in the fluid domain for flexible modelling selected Tetrahedral, and the minimum dimension on the structure surface was considered equal to 12 mm. Meshing arrangement were selected in a way that around the structure there was a smaller element, and by distancing from the structure, the size of element became larger (Figure 3-49). The total numbers of the element in the fluid part were 623357, and in the structural part, the numbers of the nodes and elements were 1429 and 190, respectively.

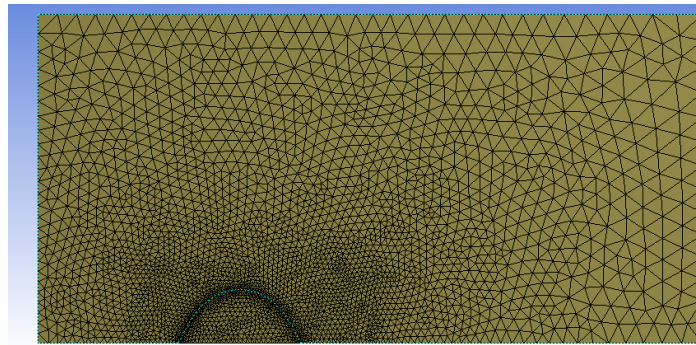


Figure 3-49: Domain and structure's meshing

3.4.2.3. Properties of Air Flow

Fluent allows users to copy materials from a database, create new materials and subsequently modify material properties. Considering the simulation of airflow around a structure, the properties should be similar to the airflow applied in the wind tunnel. Table 3-11 defined the properties of airflow.

Table 3-11: Properties of airflow.

Density (kg / m^3)	1.1687
Temperature ($^{\circ}C$)	29
Viscosity ($kg / m / s$)	1.863E-05

3.4.2.4. Boundary Conditions

In every computational fluid dynamic problem exists the need to define boundary conditions. Boundaries must first be named in the geometry and meshing modules. In the Task Boundary Condition Window, the boundary conditions such as inlet velocity, pressure, and wall were determined. The samples were modelled as shell and to reduce the size of the domain symmetry boundaries were selected. The current project has four boundary conditions, as appear in Figure 3-50 and Table 3-12.

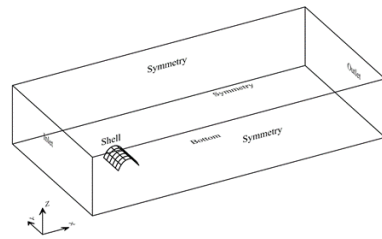


Table 3-12: Boundary condition

Bottom	Wall (no-slip)
Inlet	Velocity- inlet (UDF)
Outlet	Pressure outlet
Shell	Wall (no-slip)
Side-wall	Symmetry
Top-wall	Symmetry

Figure 3-50: Name selection on the boundary

Rigid modelling

Boundary condition in numerical modelling must be the same as what has been considered in the wind tunnel test in order to achieve the exact correlation between experimental and numerical results. Thus, the velocity profile was selected similar to the atmospheric surface layer (ASL), same as Equation 3-5:

$$U(z) = \frac{u^*}{\kappa} \ln\left(\frac{z}{z_0}\right) U_0 \quad \text{Equation 3-5}$$

Where, $U(z)$ is wind velocity in the specified height equal to z , u^* is the frictional velocity based on the structure's location equal to 0.081 m/s , k is Von Karman constants equal to 0.4 , z is desired height above ground level, z_0 is terrain roughness length (here = 0.01m) and U_0 is basic velocity equal to 10 m/s .

This equation has been introduced to the model as velocity inlet in the longitudinal direction, in the inlet section of the domain by use of UDF (this profile is shown in (a)). As it was visible, the turbulent intensity in the wind tunnel had corresponded to

Equation 3-6. In order to create the same conditions of turbulence in the wind tunnel, kinetic energy of turbulence value and energy dissipation rate profiles were calculated according to the following equations (Equation 3-7 and Equation 3-8) and were introduced into the system.

$$I(z) = \frac{1}{\ln(z/z_0)} \quad \text{Equation 3-6}$$

$$k = \frac{u^{*2}}{\sqrt{C_\mu}} = 0.02187(m^2/s^2) \quad \text{Equation 3-7}$$

$$\varepsilon = \frac{(u^*)^3}{(z + z_0) \kappa} (m^2/s^3) \quad \text{Equation 3-8}$$

Where $I(z)$ indicates the turbulence intensity in the longitudinal direction, k is the kinematic energy, C_μ is an empirical constant taken equal to 0.09, and ε is the energy dissipation rate.

Energy dissipation rate profile has been introduced to the system by use of the UDF, according to Figure 3-51(b).

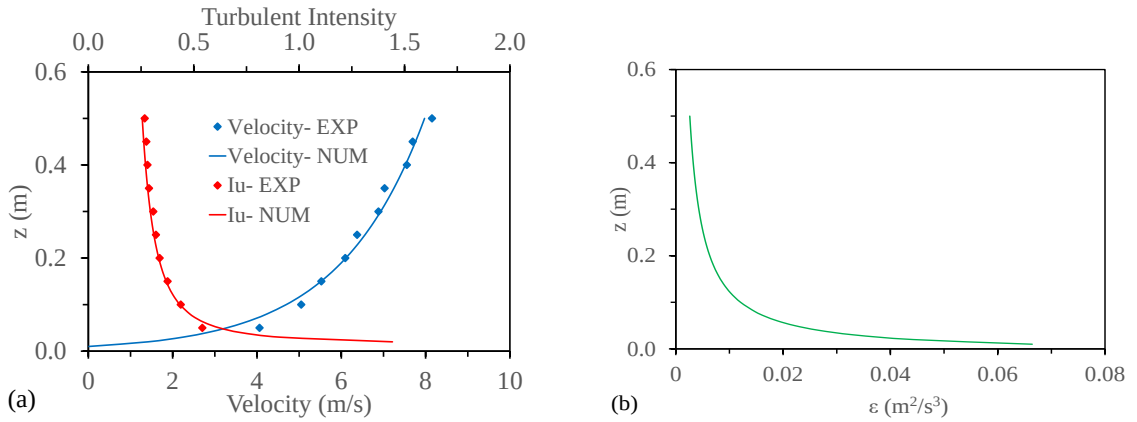


Figure 3-51: a) Velocity and Turbulent Intensity profiles, b) Energy dissipation rate profile

For other boundary condition, for the outlet section pressure was considered equal to 0 Pa, in bottom No-slip boundary condition with desired roughness height ($k_s=0.001$ m) and for other border surfaces consisted of the sidewall, symmetry condition was defined. Also, the surface of structures has been defined as No slip.

The solving method for governing equation in ANSYS fluent was applied based on the iterative Gauss-Seidel method. Based on this method, the initial value was required to start the run used from the inlet boundary. All the discretized equations were solved by using the ‘SIMPLE’ algorithm. The transient flow was considered for this simulation and the value of the time step was determined according to Courant number criteria and Equation 3-9. With selective Courant number less than 1 (Germano, 1991), the calculations were done.

$$C = \frac{U_0 \Delta t}{\Delta x} \quad \text{Equation 3-9}$$

Where C represent the Courant number, Δx is the minimum dimension of the meshing element and Δt is the time step. By considering the Courant number criteria less than 1, the time step’s value is determined to equal 0.0004 sec from 2 sec of total time.

Flexible modelling

Boundary condition in numerical modelling must be considered in the same way as the wind tunnel test so that the boundary condition would be the same as the rigid model for the fluid domain. In the structural part, two boundary conditions were defined consisted of anchor boundary condition and the border interfacing with fluid, illustrated in Figure 3-52.

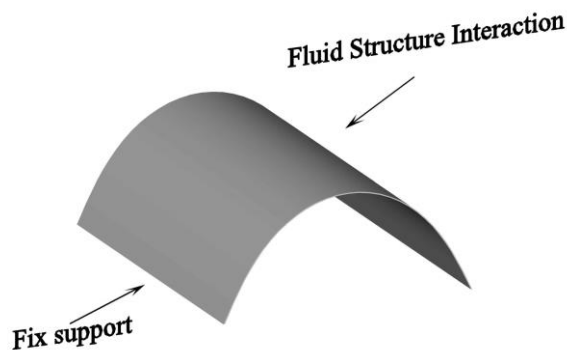


Figure 3-52: Boundary condition in the structural part

3.4.2.5. Set time step

The time step size in transient flow must be small enough to resolve time-dependent features. Considering the Courant number to be equal to 1, the magnitude of an appropriate time step size can be estimated with the following equation:

$$C = \frac{V \Delta t}{\Delta x} \xrightarrow{C=1} \Delta t = \frac{\Delta x}{V} \quad \text{Equation 3-10}$$

Here, C refers to the Courant number, Δx refers to the minimum size of the mesh element in the domain, V refers to the primary velocity and Δt refers to the time step size. The settings of the processing step in the current project were presented in Table 3-13.

Table 3-13: The settings of the processing step.

Solver	Initialization	Convergence	Set time step size (sec)
SIMPLE	Inlet	10^{-4}	0.0002

ANSYS Mechanical can utilise the material library or separately define the material properties in each analysis. The material properties of the GFRP plate used for the structure in this project are defined in Table 3-14.

Table 3-14: Material properties of the structure

Density (kg / m^3)	1723.56
Elasticity modulus (GPa)	17
Poisson ratio	0.28

3.4.2.6. Data processing

3.4.2.6.1. Mean pressure

Readings from each pressure gauge valve installed on the surface of the active bending structure were performed five times in all directions and at different wind speeds to calculate the mean pressure on the external surface of the model. According to the test time and sampling frequency of 500 Hz, a total of 20,000 points were collected in each pressure gauge valve. Thus, an average value for each pressure gauge

valve were calculated for each replicate. Using Equation 3-11, the mean pressure measured for each pressure gauge was calculated for a total of 5 experiments.

$$P_{mean} = \frac{\sum_{n=1}^n \bar{P}_n}{n}, n = 5 \quad \text{Equation 3-11}$$

In Equation 3-11, P_{mean} is mean pressure measured in each pressure gauge, $\bar{P}$ mean pressure measured in each experiment regarding each pressure gauge valve and n Indicates the number of experiments performed.

Using Equation 3-12, each pressure tap's mean pressure was obtained using the differences between the mean pressures measured from the based pressure. The base pressure is the pressure inside the wind tunnel, which measured before the wind flow was applied.

$$P_{ij} = P_{mean_{ij}} - P_0 \quad \text{Equation 3-12}$$

In Equation 3-12, P_0 Indicates base pressure, P_{mean} represent the mean pressure obtained from 5 repetitions of the experiment performed on the model at the specified angle and wind speed, and P represents mean pressure applied to the external surface of the active bending structure. P_{ij} also indicate the number and location of the pressure gauge valve. In this equation, based on Figure 3-37 the value of i is defined from A to H and the value of j is from 1 to 8.

3.4.2.6.2. Mean pressure coefficient and root-mean-square pressure coefficient (r.m.s per pressure fluctuation)

The amount and distribution of pressure on each structure were determined primarily by the structure's wind flow pattern. One of the considerable issues in the designing building was the analysis of wind flow effects and the determination of the structure's external pressure coefficient. In general, the pressure at a point was expressed using the non-dimensional value of the pressure coefficient. In structural engineering, the pressure coefficient was used to express the aerodynamic effects of a structure.

Pressure coefficients C_p are influenced by a wide range of parameters such as the building's geometry, the details and position of the components located on structures front, the type of area in which the structure had been located, and wind speed and direction (Cóstola et al, 2009).

$$C_p = \frac{P}{\frac{1}{2} \rho V_H^2} \quad \text{Equation 3-13}$$

In Equation 3-13 P is mean pressure obtained from Equation 3-11, ρ stand for air density and V_H represents design wind speed at height h .

Fluctuating, turbulence and the natural instability of airflow around bluff bodies led to separation flow and in some cases re-attachment of streamlines; thus, it creates pressure and forces which may have high fluctuations. Root-mean-square of pressure coefficient was used to indicate distributed pressure fluctuations imposed on the structure's exterior surface. The Root-mean-square pressure for each point was obtained from Equation 3-14. The root-mean-square pressure coefficient was obtained by dividing root-mean-square pressure by dynamic pressure, as shown in Equation 3-15. (ASCE/SEI49-12, 2012)

$$p_{rms} = \left(\overline{(P - P_{mean})^2} \right)^{1/2} \quad \text{Equation 3-14}$$

$$C_{p_{rms}} = \frac{p_{rms}}{q_{ref}} \quad \text{Equation 3-15}$$

3.4.2.6.3. Probabilistic Functions

Wind loads possess stochastic characteristics, especially the fluctuating component, which may force the engineering structure to flutter, torsional vibration, and other forms of wind-induced random coupling vibration. According to the theory of random process, the first four order statistical parameters, the mean, variance, skewness, and kurtosis, are the mathematical characteristics of random variables. For the random Gaussian process, the probability density function can be determined by only using the

first two-order statistics parameters (i.e., the mean and variance), while it is very difficult for the non-Gaussian stochastic process (Jiang L et al, 2018).

When wind pressure is subject to Gaussian distribution approximately, its characteristics can be completely described by the first and second order statistics. However, the researches show that wind pressure on the local region of the building roof presents obvious non-Gaussianity because of the effect of the separation, reattachment of the flow and the shedding of the vortex on the roof. At this time, it is necessary to introduce the third and fourth order statistics for further description, i.e., skewness and kurtosis. As for wind pressure coefficient time history of a tap, which is expressed by $C_P(t)$, the calculation of skewness and kurtosis is as follows:

$$C_{sk} = \frac{1}{N} \sum_{i=1}^N \{[C_P(t_i) - C_{Pmean}]/\sigma_P\}^3 \quad \text{Equation 3-16}$$

$$C_{ku} = \frac{1}{N} \sum_{i=1}^N \{[C_P(t_i) - C_{Pmean}]/\sigma_P\}^4 \quad \text{Equation 3-17}$$

In the equations Equation 3-16 and Equation 3-17, $C_P(t_i)$ ($i=1, 2, \dots, N$) stands for wind pressure coefficient of the tap at time point i . C_{Pmean} and σ_P represent the mean value and standard deviation of wind pressure coefficient, respectively. Values of skewness and kurtosis are equal to zero and three when wind pressure satisfies Gaussian distribution. When skewness is not equal to zero as well as kurtosis is not equal to three, non-Gaussianity exists to some extent for wind pressure (Luo Y et al, 2014)

3.4.2.7. Analysis of Setting

In the analysis set, the specification of the start time, end time, coupling step and minimum and maximum iteration was presented in Table 3-15. Here, it can be noted that a coupling step is the same as the time step within the transient analysis.

Table 3-15: Analysis setting at system coupling section.

End time (sec)	Coupling step (sec)	Minimum iteration	Maximum iteration
2	0.0002	1	3

CHAPTER 4

BENDING AND LOADING TEST RESULT

In this chapter, the results of laboratory and numerical modelling related to the structural behaviour of active bending structures were discussed. In the first part, the results of the bending procedure, loading laboratory experiments and temperature loading experiments are presented. In the second part, by performing numerical modelling, effective factors in the behaviour of active bending structures such as suitable materials in construction, various cross-section effect, geometry and different lengths of the structural elements are investigated.

4. Bending and Loading Test Result

4.1. Introduction

Same as any other structure, factors such as external loading and temperature, affect the behaviour of active bending structures. Therefore, laboratory experiments and numerical modelling were used to study the behaviour of bending active structures. In this chapter, results obtained from laboratory experiments and numerical modelling performed were explored.

In the first part, laboratory models were examined to investigate the behaviour of active bending structures, followed by simulating numerical models similar to laboratory models to validate the accuracy of the outcomes. For the second part, using the results gathered, numerical modelling was used to investigate other effective factors on structural behaviour under various circumstances such as cost, time, and availability which were not able to take part in laboratory experiments.

4.2. Experimental models

Internal and external forces applied to bending active structures are of paramount importance as any other structures. All bending active structures have an initial bending which creates elastic energy inside the members. The force created due to bending must be always kept within the elastic range. As in any structure, external loading is considered in bending active structures. Additionally, as factors such as temperature could affect the materials' structural behaviour, experiments were conducted to investigate the effect.

Experiments conducted in this research were divided into two main groups.

Group One: Experiments to Study Bending Active Structural Behaviour under Bending and External Point Loading

- i. Bending experiment: The main purpose of this experiment was to study the stress creation and distribution due to bending and finding the effect of various displacement on members with the care of keeping the member in elastic range.

The initial bending can simply be created by moving the joints on two ends towards each other. Also, by simulating numerical models similar to laboratory models, simulated results were verified with laboratory outcomes to examine the data's reliability. Then, using numerical modelling the factors which were not able to be examined in laboratory were investigated.

- ii. Point loading experiment: In the point loading experiment, in addition to the initial bending, a point load was applied at the crown's peak and increased and decreased incrementally. As the critical point in bending active theory is to keep the stresses created in elastic range, this test was designed to investigate the changes in stress and displacement in bending active members under external loading application. Then, by simulating numerical models similar to laboratory models' conditions, their results were compared and the reliability of the numerical results was examined. Numerical modelling was employed to the investigation of the factors which were not able to be examined in laboratory.

Group Two: Experiments to Study Bending Active Structural Behaviour under Temperature Loading

- i. Point loading after temperature loading: Temperature could affect the mechanical properties of materials; therefore, an investigation was conducted to study the effect of temperature on the bending active member's behaviour and stress distribution. After applying temperature loading to the samples, initial bending was applied, following by point loading to the crown's peak.
- ii. Tensile tests after temperature loading: As temperature could affect the material characteristics, the tests were designed to investigate the impact of temperature loading with the consideration of the effects on bending active applications. After applying temperature loading, the changes of the material's properties and its strength parameters, including modulus of elasticity and yield stress, were measured.

4.2.1. Group One Experiments

4.2.1.1. Bending Tests

In this experiment bending active models were subjected to initial bending by displacing sample's joints in a horizontal direction towards each other. The axial strain was obtained at the dedicated strain gauges' locations, and details pertaining to tests were presented in Table 4-1. Experiments were performed on circular section samples with 7.9 mm and 9.5 mm diameters and rectangular section samples of 40×5 mm and 80×8 mm. The length of all models except the Strip-2 models was 1 m and due to bending, reached the secondary spans of between 0.9 m and 0.99 mm. The length of Strip-2 models was 2 m, and reached the secondary spans of between 1.71 to 1.87 m by moving joints towards each other. To increase the reliability and control of the reversibility, each test was carried out three times, and the mean strain of three experiments was presented. Moreover, numerical modelling same as laboratory experiments was simulated and analysed.

Table 4-1: Bending tests

Test No	Sample	Original Length (m)	Secondary Span (m)
1-1	Circle-1	1	0.9
1-2	Circle-1	1	0.97
1-3	Circle-1	1	0.98
1-4	Circle-1	1	0.99
1-5	Circle-2	1	0.97
1-6	Circle-2	1	0.98
1-7	Circle-2	1	0.99
1-8	Strip-2	2	1.71
1-9	Strip-2	2	1.80
1-10	Strip-2	2	1.87
1-11	Strip-1	1	0.9

4.2.1.2. Point Loading Tests

In the point loading experiment, at first, the initial bending was applied to the models, then a pressure jack was used to apply point loading to the crown's peak. Loading was increased and decreased incrementally, and the axial strain created in the gauges was measured during the experiment. To ensure the reliability of test and results obtained, three experiments were repeated in each section and the mean value within four standard deviations was presented. Since the load was applied with a displacement control jack, it was not possible to perform repetitive experiments with fixed loadings. Therefore, to have comparable results, equal displacements were applied each time. The experiments' details are presented in Table 4-2. In the loading step, the 1 m samples reached to a secondary span of 0.9 m after initial bending, and 2 m samples reached to a secondary span of 1.8 m. The values of point loading in each test are shown in the last column of Table 4-2. As an example, in Test 2-1, three point loads of 107, 180, and 190 N were applied; in Test 2-7, the point loading increased from 65 to 730 N and then underwent a gradual release. To use verified models to explore designs, numerical models under same laboratory conditions were simulated and results from both laboratory experiments and numerical simulations were compared and analysed.

Table 4-2: Bending and loading

Test No	Sample	Length (m)	Final Span (m)	Point Load (N)
2-1	Circle-1	1	0.9	107-180-190
2-2	Circle-1	1	0.9	191-330-241
2-3	Circle-1	1	0.9	193-330-242
2-4	Circle-2	1	0.9	150-336
2-5	Circle-2	1	0.9	231-405-304
2-6	Circle-2	1	0.9	234-404-303
2-7	Strip-1	1	0.9	65-350-500-650- 730-640-522-353
2-8	Strip-1	1	0.9	235-356-281
2-9	Strip-1	1	0.9	233-357-279
2-10	Strip-2	2	1.8	265-447-337
2-11	Strip-2	2	1.8	267-448-337
2-12	Strip-2	2	1.8	263-446-338

4.2.2. Group Two Experiments

In this experiment, members were subject to temperature loading using target and cyclic temperature loading prior to bending and point loading to investigate the effect of temperature changes on material characteristics and stress distribution.

4.2.2.1. Tensile Tests

Subsequently, to conduct the tensile test, 1 m samples subjected to temperature changes were cut into 0.4 m long pieces. These samples were examined using Universal Test Machinery to measure the modulus elasticity and yield stress. To ensure reliability of the results obtained, three experiments were completed for each case. For majority of the experiments, results for each group (three examples) were almost equal and very limited differences in the results were observed in some cases. Following this, the value of the desired parameters was the mean value within four standard deviations of three experiments. Details pertaining to the performed tests of different samples are shown in Table 4-3.

Table 4-3: Samples details (Tension test)

Test No.	Sample	Length (m)	Temperature (°C)
3-1	Strip-1	0.4	-5
3-2	Strip-1	0.4	0
3-3	Strip-1	0.4	10
3-4	Strip-1	0.4	20
3-5	Strip-1	0.4	30
3-6	Strip-1	0.4	40
3-7	Strip-1	0.4	50
3-8	Strip-1	0.4	Type 1
3-9	Strip-1	0.4	Type 2
3-10	Circle-1	0.4	-5
3-11	Circle-1	0.4	0
3-12	Circle-1	0.4	10
3-13	Circle-1	0.4	20
3-14	Circle-1	0.4	30
3-15	Circle-1	0.4	40
3-16	Circle-1	0.4	50
3-17	Circle-1	0.4	Type 1
3-18	Circle-1	0.4	Type 2

4.2.2.2. Point Loading Tests

After subjecting samples to temperature changes, point loads were applied in several steps. Details of the experiments performed on different models are presented in Table 4-4.

Table 4-4: Tests including point loading after temperature changes

Test No.	Sample	Length (m)	Temperature (°C)	Load (N)
4-1	Strip-1	1	0	227-362-254
4-2	Strip-1	1	0	230-361-256
4-3	Strip-1	1	0	225-362-251
4-4	Strip-1	1	50	246-356-285
4-5	Strip-1	1	50	249-356-284
4-6	Strip-1	1	50	243-355-287
4-7	Strip-1	1	Type 1	329-375-264
4-8	Strip-1	1	Type 1	327-376-265
4-9	Strip-1	1	Type 1	329-377-262
4-10	Strip-1	1	Type 2	284-341-226
4-11	Strip-1	1	Type 2	285-341-227
4-12	Strip-1	1	Type 2	282-342-229
4-13	Circle-1	1	0	188-346-250
4-14	Circle-1	1	0	197-347-247
4-15	Circle-1	1	0	186-345-251
4-16	Circle-1	1	50	217-321-260
4-17	Circle-1	1	50	220-322-262
4-18	Circle-1	1	50	216-323-261
4-19	Circle-1	1	Type 1	228-378-304
4-20	Circle-1	1	Type 1	230-378-306
4-21	Circle-1	1	Type 1	225-380-302
4-22	Circle-1	1	Type 2	230-323-283
4-23	Circle-1	1	Type 2	227-324-284
4-24	Circle-1	1	Type 2	228-326-282

4.2.3. Results

A summary of the experimental results is presented in the following for each experiment. In order to better display the results, all strain values were multiplied by 1000. Meanwhile, some of the gauges were detached from the samples during testing or damaged by being located just under the loading jack. It must be noted that these gauges faced errors in functioning; thus, malfunctioning gauges were omitted from the procedure.

4.2.3.1. Bending Tests

In bending experiments, samples were gently bent by joints' displacements and after reaching the desired secondary span (form-finded geometry), the results were captured, and the samples were gradually gone back to its original position (Group One tests). Laboratory outputs and numerical modelling results are presented separately.

Laboratory and Numerical Results for Circle-1

Bending results from the Circle-1 experiment are presented in Table 4-5. The secondary span was considered in 4 different modes of 0.99, 0.98, 0.97 and 0.9 m. Negative values in the strain gauges located at the bottom of the sample indicated compressive strain. Positive values indicated the tensile strain in the strain gauges located at the upper web. As the samples bent, strain created at the top of the sample' curve increased, which made strain created in position B greater than strain created in position A and C (Figure 3-6). Also strain value was symmetrically distributed in the position A and C on the models. For example, the upper web's strain values in model 1-1, in position A and C were equal to 1.5, and in position B was equal to 7.2. Also, it is noted that the smaller secondary span led to a greater strain. For instance, the strain values in the B-top strain gauge in models 1-1, 1-2, 1-3 and 1-4 were equal to 7.2, 4.0, 3.5 and 2.1, respectively. Based on the results presented, the strain values obtained from the experiments were similar to the values obtained from the numerical modelling and the differences were considered reasonable.

Table 4-5: Experimental and Numerical Results for Circle-1 (Bending)

Model No.	1-1		1-2		1-3		1-4	
Final Span (m)	0.9		0.97		0.98		0.99	
Aspect Ratio (f/L)	0.21		0.11		0.09		0.06	
Node	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM
A-top	5.1	4.9	3.6	2.6	2.8	2.1	1.6	1.4
A-bot	-5.4	-5.2	-3.5	-2.8	-2.8	-2.3	-1.7	-1.6
B-top	7.2	7.0	4.0	3.7	3.5	2.9	2.1	2.0
B-bot	-7.4	-7.3	-4.4	-3.9	-3.7	-3.1	-2.3	-2.1
C-top	5.1	4.9	3.6	2.6	2.8	2.1	1.8	1.4
C-bot	-5.3	-5.2	-3.5	-2.8	-2.8	-2.3	-1.7	-1.6
Point: The scale of the numbers is 1000.								

Table 4-6 provided an example of obtaining mean value for each test by using the empirical rule which presented the method of calculating around 95% of scores within four standard deviations of the mean for three repeated tests.

Table 4-6: Empirical rule

Node	Test 1	Test 2	Test 3	SD	M	M+2SD	M-2SD
A-top	5.07	5.09	5.11	0.02	5.1	5.1	5.1
A-bot	-5.42	-5.39	-5.41	0.01	-5.4	-5.4	-5.4
B-top	7.18	7.17	7.19	0.01	7.2	7.2	7.2
B-bot	-7.37	-7.39	-7.41	0.02	-7.4	-7.4	-7.4
C-top	5.08	5.09	5.12	0.02	5.1	5.1	5.1
C-bot	-5.28	-5.28	-5.30	0.01	-5.3	-5.3	-5.3
Point: The scale of the numbers is 1000.							

Laboratory and Numerical Results for Circle-2

Table 4-7 presents results for Circle-2 with secondary spans of 0.99, 0.98 and 0.97 m. The strain values grew with shortening secondary span. For example, the A-bot values range from 2.4 in Models 1-7 to 3.2 and 3.8 in Models 1-6 and 1-5, respectively. On the other hand, the strain values in the C-bot in Models 1-7, 1-6 and 1-5 were equal to 2.4, 3.2 and 3.8 which were precisely equal to the values in the A-bot, indicating the reliability of the experimental tests. The strain created due to bending, increased

towards the top part of the sample, which made the strain in position B greater than the strain in positions A and C. Also, it indicated that the greater the f/L was the greater strain in the samples was measured.

Table 4-7: Experimental and Numerical Results for Circle-2 (Bending)

Model No.	1-5		1-6		1-7	
Final Span (m)	0.97		0.98		0.99	
Aspect Ratio (f/L)	0.11		0.09		0.06	
node	EXP	NUM	EXP	NUM	EXP	NUM
A-top	3.6	3.1	3.3	2.5	2.4	1.7
A-bot	-3.8	-3.3	-3.2	-2.7	-2.4	-1.9
B-top	5.2	4.4	4.4	3.5	3.2	2.3
B-bot	-4.6	-4.6	-4.6	-3.7	-3.3	-2.5
C-top	3.6	3.1	3.3	2.5	2.5	1.7
C-bot	-3.8	-3.3	-3.2	-2.7	-2.4	-1.9
Point: The scale of the numbers is 1000.						

Laboratory and Numerical Results for Strip-1

Table 4-8 presents results of Strip-1 (Experiments 1-11). The strain created in positions A and C were equal and smaller than the strain in position B. The strain on the upper web were measured as 3.9 at positions A and C and 4.5 at position B. These values in the numerical model were equal to 3.2 and 4.5, respectively. It was witnessed that the strain in position B was exactly equal to the strain obtained from experimental test, but in positions A and C, there was an error of about 17%.

Table 4-8: Experimental and Numerical Results for Strip-1 (Bending)

Model No.	1-11	
Final Span (m)	0.9	
Aspect Ratio (f/L)	0.21	
node	EXP	NUM
A-top	3.9	3.2
A-bot	-3.8	-3.3
B-top	4.5	4.5
B-bot	-4.6	-4.7
C-top	3.9	3.2
C-bot	-3.8	-3.3
Point: The scale of the numbers is 1000.		

Laboratory and Numerical Results for Strip-2

Results for the 2 m models with the secondary spans of 1.71, 1.80 and 1.87 m are presented in Table 4-9. The strain in all strain gauges increased with decreasing secondary span's length, similar to other experiments. Stresses obtained in locations A and C in both experimental and numerical tests were almost equal with slight discrepancies. Although the test results varied with the changes of cross-section and length, the general trend of the strain creation in the samples was similar.

Table 4-9: Experimental and Numerical Results for Strip-2 (Bending)

Model No.	1-8		1-9		1-10	
Final Span (m)	1.71		1.80		1.87	
Aspect Ratio (f/L)	0.27		0.21		0.16	
node	EXP	NUM	EXP	NUM	EXP	NUM
A-top	3.2	2.9	2.8	2.4	2.2	1.9
A-bot	-3.3	-3.0	-3.0	-2.4	-2.1	-1.9
B-top	4.5	4.1	3.8	3.4	2.9	2.6
B-bot	-4.6	-4.3	-3.8	-3.5	-3.0	-2.7
C-top	3.2	2.9	2.8	2.4	2.2	1.9
C-bot	-3.3	-3.0	-3.0	-2.4	-2.1	-1.9
Point: The scale of the numbers is 1000.						

4.2.3.2. Point Loading Tests

To investigate the effect of point loading on bending active members, a point load was incrementally applied to the middle of bent samples, and also numerical modelling was simulated with same conditions as experimental tests.

Experimental and Numerical Results for Circle-1; Models 2-1 to 2-3

Results from the Circle-1 with the original length of 1 m, which reached to the secondary span of 0.9 m due to bending are presented in Table 4-10 . In Test 2-1, point loads of 107, 180, and 190 N were applied to the sample. In the whole process of loading, the strain values in position A and C were equal. Respectively, the strain increased with increasing point load and decreased during unloading. At the A-top, the strain value after initial bending was equal to 5.0, and increased to 6.3 as a result of applying a 107 N point load. This growth in strain values observed not only in 180 N

but also in the tests with 190 N point loads. Furthermore, by unloading, it reached the initial value of 5.0.

Equality in strain's values before applying point load and after removing point load demonstrated the model's elastic behaviour and reversibility and indicated the reliability of measuring strains in experimental test to ensure the plastic strain was zero. Also, results for Tests 2-2 and 2-3 are presented Appendix C-1.

Table 4-10: Numerical and Experimental Results of Circle-1 at the point loading step (model 2-1)

Point Load (N)	0		107		180		190		0	
node	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM
A-top	5.0	4.9	6.3	5.9	7.5	6.7	7.8	6.9	5.0	4.9
A-bot	-5.0	-5.2	-6.4	-6.3	-7.6	-7.3	-7.7	-7.5	-5.0	-5.2
B-top	6.3	7.0	2.5	2.6	1.9	1.8	1.7	1.6	6.3	7.0
B-bot	-6.4	-7.3	-2.2	-2.7	-2.0	-2.0	-1.8	-1.7	-6.4	-7.3
C-top	5.0	4.9	6.4	5.9	7.5	6.7	7.8	6.9	5.0	4.9
C-bot	-5.1	-5.2	-6.3	-6.3	-7.5	-7.3	-7.7	-7.5	-5.1	-5.2
Point: The scale of the numbers is 1000.										

Experimental and Numerical Results for Model Circle-2; Model 2-4 to 2-6

During point loading procedure, Circle-2 model with 1 m length reached to the secondary span of 0.9 m, then, point loads of 150 N and 336 N were applied to the sample incrementally. By applying point loads, the strain in positions A and C increased and on the contrary decreased in position B. Results indicated that the maximum stress was transferred from the centre of the model to the sides by applying a point load to the model's crown. The strain at A-top and C-top in the initial bending step were 6.2 and 6.0. Due to the experiments similarity, only results for experiments 2-4 are presented here, and results for experiments 2-5 and 2-6 are included in Appendix C-2.

Table 4-11: Numerical and Experimental Results of Circle-2 at the point loading step (model 2-4)

Point Load (N)	0		150		336		0	
Node	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM
A-top	6.2	5.9	6.6	6.8	7.9	8.2	6.2	5.9
A-bot	-4.7	-6.2	-5.3	-7.2	-6.3	-8.9	-4.7	-6.1
B-top	7.4	8.4	4.9	6.1	0.0	2.6	7.4	8.4
B-bot	-7.3	-8.7	-4.9	-6.7	0.0	-3.5	-7.3	-8.7
C-top	6.0	5.9	6.6	6.8	7.9	8.2	6.0	5.9
C-bot	-4.7	-6.2	-5.3	-7.2	-6.3	-8.9	-4.7	-6.1
Point: The scale of the numbers is 1000.								

Experimental and Numerical Results for Strip-1; Models 2-7 to 2-9

In this section, strip samples were studied under point loading. Table 4-12 presents results for Model 2-7. Strip-1 model with 1 m length and secondary span of 0.9 m were loaded with 65, 350, 500, 650, and 730 N single loads and unloaded to 640, 522, 353, and 0 N. The strain at B-top in the initial bending, was equal to 3.9. With applying point loads, the strain reached zero at 500 N. With increasing the point load, the strain at the B-top became negative and reached -2.9 under 730 N load. This implies that at B-top, the tensile strain caused by the initial bending became a compressive strain due to increases in the point load (in upper web). In return, it indicated that as point load increased the initial arc shape changed and maximum stress was transferred from the middle of the member toward the joints. It can also be observed that the strain created in positions A and C were equal in most steps. The major differences in experimental and numerical modelling were observed at B-bot. This difference occurred at the initial bending step, and considering that the strain results were in cumulative form and were the sum of the strains created in previous steps, the differences emerged in later steps. Also, results for Tests 2-8 and 2-9 are attached in appendix C-3.

Table 4-12: Numerical and Experimental Results of Strip-1 at the point loading step (Model 2-7)

Point Load (N)	0		65		350		500		650	
Node	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM
A-top	3.1	2.9	3.2	3.0	3.8	3.9	4.4	4.5	4.7	5.5
A-bot	-2.9	-3.0	-3.0	-3.2	-3.9	-4.4	-4.3	-5.2	-4.8	-6.4
B-top	3.9	4.0	3.5	3.6	1.3	1.4	0.0	-0.2	-1.8	-2.5
B-bot	-3.8	-4.4	-3.4	-4.0	-1.4	-2.0	-0.1	-0.5	1.6	1.5
C-top	3.1	2.9	3.2	3.0	4.0	3.9	4.4	4.5	4.9	5.5
C-bot	-3.2	-3.0	-3.3	-3.2	-3.9	-4.4	-4.3	-5.2	-4.8	-6.4
Point Load (N)	730		640		522		353		0	
Node	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM
A-top	5.1	6.3	4.7	5.4	4.5	4.6	3.8	3.9	3.1	2.9
A-bot	-5.1	-7.4	-4.7	-6.3	-4.3	-5.4	-3.9	-4.4	-2.9	-3.0
B-top	-2.9	-4.5	-1.9	-2.3	-0.6	-0.5	1.0	1.4	3.6	4.1
B-bot	2.8	3.2	1.7	1.3	0.5	-0.3	-1.0	-1.9	-3.6	-4.3
C-top	5.2	6.3	4.9	5.4	4.5	4.6	4.1	3.9	3.1	2.9
C-bot	-5.1	-7.4	-4.7	-6.3	-4.3	-5.4	-3.9	-4.4	-3.1	-3.0
Point: The scale of the numbers is 1000.										

Experimental and Numerical Results for Strip-2; Models 2-10 to 2-12

Table 4-13 presents results for Model 2-10, and the results for Models 2-11 and 2-12 are attached in Appendix C-4. Through experimenting Strip-2, the model with 2 m length reached the secondary span of 1.80 m, and point loads of 265, 447 and 337 N were applied to the sample incrementally. Similar to the experiments tested, with increasing the point load, the strain at the arc's crown (B-Top) decreased.

Table 4-13: Numerical and Experimental Results of Strip-2 at the point loading step (model 2-10)

Point Load (N)	0		265		447		337		0	
Node	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM	EXP	NUM
A-top	2.5	2.4	3.2	3.1	3.8	3.9	3.5	3.4	2.5	2.4
A-bot	-2.5	-2.4	-3.5	-3.3	-4.2	-4.1	-3.8	-3.6	-2.5	-2.4
B-top	3.3	3.4	1.7	1.9	0.3	0.4	1.5	1.4	3.3	3.4
B-bot	-3.3	-3.5	-1.8	-1.6	0.1	0.1	-1.1	-1.0	-3.3	-3.5
C-top	2.5	2.4	3.2	3.1	3.8	3.9	3.5	3.4	2.5	2.4
C-bot	-2.5	-2.4	-3.5	-3.3	-4.2	-4.1	-3.8	-3.6	-2.5	-2.4
Point: The scale of the numbers is 1000.										

4.2.3.3. Tensile Tests after Temperature Loading

To measure the modulus of elasticity and yield stress of samples, tensile tests were performed. Firstly, all samples were subjected to temperature changes in two different methods, target temperature change and cyclic temperature loading. In order to determine samples' yield stress, test was continued until full rupture. The modulus of elasticity of the tested materials was attained from the stress-strain diagram. Three tests were performed for each thermal condition to maximise the precision in laboratory results. The modulus of elasticity and the yield stress under different thermal conditions for circle and strip cross-section samples are presented in Table 4-14.

Table 4-14: Tension Tests

Test	Sample	Temperature (°C)	E (GPa)	Yield stress (MPa)
3-1	Strip-1	-5	16.5	170
3-2	Strip-1	0	16.8	170
3-3	Strip-1	10	17.0	170
3-4	Strip-1	20	17.0	170
3-5	Strip-1	30	17.0	170
3-6	Strip-1	40	17.5	160
3-7	Strip-1	50	17.5	155
3-8	Strip-1	Type 1	20	145
3-9	Strip-1	Type 2	18	152
3-10	Circle-1	-5	29.2	550
3-11	Circle-1	0	29.4	550
3-12	Circle-1	10	30	550
3-13	Circle-1	20	30	550
3-14	Circle-1	30	30	550
3-15	Circle-1	40	30.5	540
3-16	Circle-1	50	30.8	530
3-17	Circle-1	Type 1	35.0	480
3-18	Circle-1	Type 2	32.0	500

It can be concluded that in the results presented in Table 4-14, samples appear to behave differently under various temperatures. In strip cross-sectional samples under

target temperature loading (one cycle), the modulus of elasticity in strip samples reduced to 16.5 GPa at -5°C and 16.8 GPa at 0°C . The sample's modulus of elasticity at temperatures 10, 20 and 30°C was equivalent to the modulus of elasticity at ambient temperature (24°C - 17 GPa). As the temperature rose to 40°C and 50°C , the modulus of elasticity increased, reaching 17.5 GPa. Yield stress in strips at ambient temperature was equal to 170 MPa. As shown in Table 4-14, the yield stress value from -5°C to 30°C was equal to 170 MPa which implied that the decreasing temperature did not influence the yield stress. With increasing temperatures to 40°C and 50°C , yield stress reduced to 162 MPa and 158 MPa, respectively.

In circular cross-section specimens, the modulus of elasticity of samples under temperature loading reduced to 29.2 GPa at -5°C and 29.4 GPa at 0°C . At temperatures of 10, 20 and 30°C , the modulus of elasticity was recorded equal to the modulus of elasticity at ambient temperature, 30 GPa. With increasing temperature to 40°C , the modulus of elasticity reached 30.5 GPa and finally at 50°C , it rose to 30.8 GPa. As previously illustrated the trend in strips, the yield stress in the circular sections had no change under applied temperatures from -5°C to 30°C and was equal to 550 MPa. By increasing the temperature and reaching 40°C its value changed to 540 GPa and 530 GPa at 50°C .

It can be interpreted that the modulus of elasticity decreased slightly by decreasing the temperature and some changes occurred as temperature rose. In numerical modelling, the value of modulus of elasticity used as equal to the initial value. These changes of modulus of elasticity are represented in Figure 4-1. On the other hand, with decreasing temperature no changes occurred in yield stress. As the temperature increased, the yield stress decreased slightly at 40°C and 50°C . This indicated that samples in high temperatures could reach plastic mode under less stain. Figure 4-2 presents changes in modulus of elasticity and yield stress at different temperature.

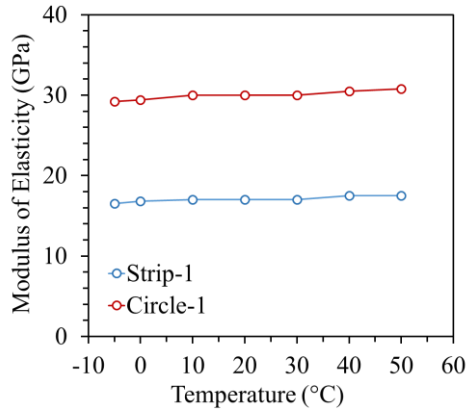


Figure 4-1: The elasticity modulus changes under different target temperature

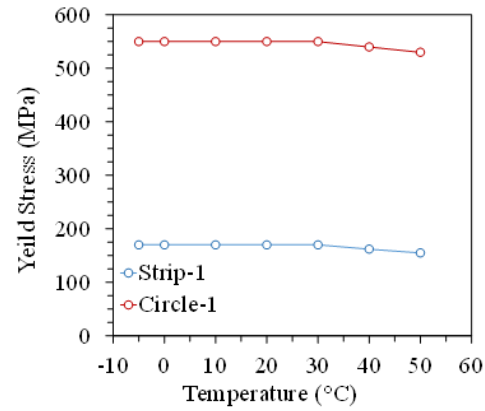


Figure 4-2: The yield stress changes under different target temperature

According to the results obtained from tensile testing on strip samples, the elastic modulus after applying Type 1 temperature (Figure 3-21) was equal to 20 GPa. Under Type 2 (Figure 3-21) temperature loading, the elastic modulus changed to 18 GPa. In circular cross-sectional samples, the modulus of elasticity reached 35 GPa under Type 1 temperature loading and 32 GPa at Type 2 temperature cyclic pattern. Figure 4-3 presents modulus of elasticity changes concerning the cyclic temperature loading. It could be observed from laboratory experiments that cyclic temperature loading had impact on the material's modulus of elasticity. The greater the temperature difference was in cycles, the more significant changes occurred in the modulus of elasticity, which ultimately made the material behaviour more fragile in the elastic range. Forty eight cycles were applied to samples in both cyclic loading patterns and in case of changes in the number of cycles, there is a possibility that different behaviour could be obtained.

Figure 4-4 presents the changes in yield stress due to cyclic temperature change. According to the results obtained after applying temperature cycles, materials' yield stress decreased, and the higher temperature fluctuations caused lower yield stress. In Type 1 pattern, the strips' yield stress value was 140 MPa and in rebar recorded as 480 MPa. Also, in Type 2 cyclic loading, the yield stress value in strips was equal to 150 MPa and in the rebar was equal to 500 MPa.

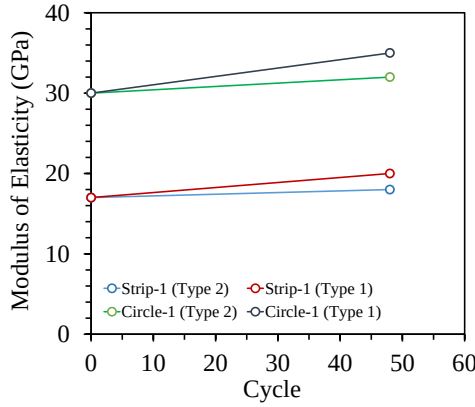


Figure 4-3: Elastic modulus changes concerning temperature cycles

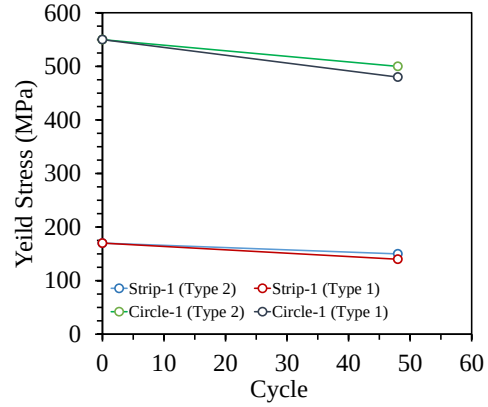


Figure 4-4: Yield stress changes with respect to temperature cycles

4.2.3.4. Point Loading Results after Cyclic Temperature Loading

Within this section, to gain a better understanding of bending active behaviour under various situations, attempts were made to apply point loading on bending active models, which were affected by temperature loading. In these experiments, 1 m long samples were subjected to temperature loading. By displacing the joints and reaching to the secondary span of 0.9 m, samples were undergone initial bending. Afterwards, by applying point load on the crown's peak, the axial strain was computed for the six positions where the strain gauges were installed. As the elasticity modulus changes were almost equal in most parts, only the secondary temperature of 0°C and 50°C were checked for both Strip-1 and Circle-1 models. The point loading was applied increasingly in two steps and then decreased in one step and entirely removed at the final stage. To investigate the differences between experimental findings and numerical modelling results, numerical models were simulated using the same criteria as the experimental tests and the loading steps were applied according to the performed experiments. Based on the findings from experimental tests, the elasticity modulus changes for temperature variations points to point was very limited; therefore, it was taken as 17 GPa for strip samples and 30 GPa for circle samples as in an ambient temperature. In the cyclic temperature loading, the modulus of elasticity of temperature loaded strip samples at Type 1 temperature cycle was obtained 20 GPa and 18 GPa for Type 2 temperature cycle pattern. Similarly, for the circle cross-section samples, the

elasticity modulus in temperature loading Type 1 was considered 35 GPa and 32 GPa for Type 2. Three tests were carried out for each case to maximize reliability of findings. As stated earlier, due to some limitations in the pressure jack for the application of point loading, it was not possible to run tests with equal point loading. Consequently, attempts were made to retain the displacement applied to the arc's crown. Details of strain and point loading values in each experiment are provided separately in Appendix C-5. In summary, the strain values generated in the two strain gauges of A-top and B-bot for the maximum loading and unloading stages were investigated. Table 4-15 and Table 4-16 present the experimental and numerical outcomes for Strip-1 and Circle-1 models under point loading. Several models failed under loading as they became brittle, and therefore, the experiments continued with less load applied for new samples. This suggested that by applying temperature changes to GFRP materials, apart from the changes in the modulus of elasticity, other properties of the material were affected which made the samples more brittle. Thus, these caused a restriction in bending and point loading, which resulted in structures' defects.

Table 4-15: Numerical and laboratory point loading results of Strip-1 model after temperature loading (target pointed and cyclic)

test	Loading					Unloading				
	Load (N)	A- top		B-bot		Load (N)	A- top		B-bot	
		EXP	NUM	EXP	NUM		EXP	NUM	EXP	NUM
4-1	362	6.2	6.1	3.1	3	254	4.7	4.6	-0.3	-0.2
4-2	361	6.2	6.1	2.8	2.9	256	4.8	4.7	-0.6	-0.4
4-3	362	6.2	6.1	3.2	3	251	4.8	4.6	-0.5	-0.3
4-4	356	6.1	6	2.8	2.7	285	5.1	5	0.7	0.6
4-5	356	6.2	6	2.9	2.8	284	5.2	5	0.7	0.5
4-6	355	6.2	6	2.6	2.7	287	5.2	5	0.8	0.6
4-7	375	5.5	5.4	1.6	1.5	264	4.2	4.4	-0.9	-0.8
4-8	376	5.2	5.4	1.3	1.5	265	4.2	4.4	-0.9	-0.8
4-9	377	5.2	5.4	1.6	1.5	262	4.4	4.3	-0.8	-0.9
4-10	341	5.2	5.4	1.7	1.6	226	4.5	4.3	-1.2	-1.1
4-11	341	5.6	5.5	1.5	1.6	227	4.4	4.3	-1.1	-1
4-12	342	5.3	5.5	1.5	1.6	229	4.6	4.3	-1.2	-1
Point: The scale of the numbers is 1000.										

Table 4-16: Numerical and laboratory point loading results of Circle-1 model after temperature loading (target pointed and cyclic)

test	Loading					Unloading				
	Load (N)	A- top		B-bot		Load (N)	A- top		B-bot	
		EXP	NUM	EXP	NUM		EXP	NUM	EXP	NUM
4-13	346	10.3	10.2	4.9	4.8	250	8.0	7.9	-0.4	-0.3
4-14	347	10.4	10.3	4.8	4.9	247	7.9	7.8	-0.5	-0.4
4-15	345	10.4	10.2	4.7	4.8	251	7.7	7.9	-0.3	-0.2
4-16	321	9.5	9.4	3.3	3.1	260	8.2	8	0.3	0.1
4-17	322	9.3	9.5	3.1	3.2	262	8.0	8.1	0.1	0.2
4-18	323	9.4	9.5	3.3	3.3	261	8.2	8.1	0.3	0.2
4-19	378	9.6	9.5	3.4	3.3	304	8.2	8.1	0.3	0.2
4-20	378	9.6	9.5	3.5	3.4	306	8.0	8.1	0.3	0.2
4-21	380	9.5	9.6	3.5	3.4	302	8.2	8	0.3	0.1
4-22	323	9.2	9	2.4	2.2	283	8.4	8.2	0.5	0.4
4-23	324	9.1	9	2.4	2.2	284	8.3	8.2	0.5	0.4
4-24	326	9.1	9	2.5	2.3	282	9.0	8.1	0.5	0.3
Point: The scale of the numbers is 1000.										

4.2.4. Results Summary

Laboratory tests are necessary to study bending active structures' behaviour under different conditions including bending, external loading, and changes in environmental conditions, such as temperature. Therefore, the various effective factors were examined in the laboratory tests.

4.2.4.1. Bending Tests Results

In bending experiments, by applying displacement to the joints, initial bending was created, and the value of the axial strains was computed at the desired locations using strain gauges. Outcomes from experimental tests enable the evaluations of active bending structures under initial bending. Based on the experiments performed, the following findings were obtained:

- After applying the displacement to the supports, the models were subjected to the internal stresses resulted from bending. The upper web was subjected to tensile stress, and the lower web was under compression stress.

- The stresses created in the samples increased by increasing displacement. This meant that the stresses created were greater in models with an equal cross-sectional area and smaller end span length.
- Given that the displacement on the supports was symmetrically applied, the strain created in samples were symmetrically equal.

4.2.4.2. Point Loading Test Results

In the point loading experiments, the initial bending was applied to the models by joints displacement followed by point loading applied incrementally to the arc's crown using a pressure jack. In this experiment, the axial strain created at the site of strain gauges and the point load at different steps were measured. Among the important results of this experiment are listed as following:

- Before applying the point load, the models were subjected to the stress resulting from the bending stage; thus, the upper web was under tension and the lower web was compressed.
- By applying load to the arc's crown, the stress distribution changed in the samples. With the increase in point loading, the strain values increased at points A and C, while at point B, the strain decreased. In the case of increasing point loading to a certain extent, the strain at point B in the upper web varied from positive to negative and in the lower web from negative to positive. Therefore, at this point, the upper web moved from the tensile zone and entered the compression zone. As an example, this can be seen in Model 2-7, that by applying point load, strain at point B was gradually reduced, and as the point load exceeded 500 N, the direction of the strain changed.

4.2.4.3. Tensile Tests after Temperature Loading Results

In the tensile testing section, after temperature loading on the laboratory samples, the tensile test was performed. Temperature loading was applied in two diverse manners. In the first case, the samples' temperature reached secondary temperature

from the ambient temperature, and in the second case, samples were subjected to cyclic temperature loading.

The modulus of elasticity and yield stress changes for the samples undergone temperature loading are as following:

- As the samples were subjected to temperature changes, the modulus of elasticity varied with the original state. The modulus of elasticity at ambient temperature for strips was 17 GPa and for rebars was 30 GPa, while at -5°C for strips changed to 16.5 GPa and 29.2 GPa for rebars. The modulus of elasticity at the highest temperature tested (50°C), in strips, reached 17.5 GPa and in rebar was recorded 30.8 GPa.
- The yield stress for samples under temperature changes from 5°C to 30°C was equivalent to ambient temperature and equal to 170 MPa for strips and 550 MPa for rebars. As the temperature increased, material's yield stress decreased, which at 50°C , the yield stress in strips reduced to 155 MPa and in rebar to 530 MPa.
- In the case of cyclic temperature loading, the effects in modulus of elasticity and yield stress were more significant than the target temperature loading. The greater the temperature difference is in the cycles, the greater changes in the modulus of elasticity are obtained.
- According to the results obtained from cyclic temperature loading, the strips' modulus of elasticity in pattern Type 1 was equal to 20 GPa, and in pattern Type 2 was evaluated as 18 GPa. This value was equal to 35 GPa in rebar for pattern Type 1 and 33 GPa for pattern Type 2.
- The yield stress obtained for strip samples after being subjected to cyclic temperature under Type 1 loading reduced to 140 MPa and 150 MPa in Type 2 loading. Also, the yield stress for rebar in Type 1 loading reduced to 480 MPa, and in Type 2 loading reached to 500 MPa.

Results obtained from temperature loading indicated that the GFRP materials behaviour and resistance parameters were influenced by temperature loading. So that with applying temperature change based on target temperature loading, the modulus of

elasticity and yield stress did not changed significantly. However, with temperature changes cyclically, the material's characteristics become more brittle, and the range of elastic behaviour decreased, which is a considerable aspect in bending active theory. As the behaviour of active bending structures is defined only in the elastic range, by increasing the modulus of elasticity and decreasing the yield stress of materials, the stress created in the samples increased, and the structure would enter the plastic range via less stress. Therefore, it should be considered in the process of design and applications of active bending structures.

4.2.4.4. Point Loading Tests after Temperature Loading Results

In this part of the research, there was an attempt made to investigate the behaviour of temperature loaded samples under external loading.

- With the application of temperature loading on the bending active structures, materials' behaviour became more brittle. Therefore, in several experiments during the loading procedure, some samples were cracked or failed during the tests. This reflected the effects of temperature on the elastic behaviour of materials. With reducing the elastic behaviour of materials, bending active members' reversibility was affected, which may disrupt their main function.
- Comparing laboratory results with numerical modelling, it was observed that the selected procedure was appropriate, and the difference between numerical and laboratory results was within a reasonable range. As a result, this process can be used with great precision in numerical modelling of complex bending active structures.

4.3. Numerical Modelling

Numerical modelling is one of the alternative methods used to investigate structures' behaviour, especially in cases where operating laboratory experiments are not feasible. In this section, various numerical models were developed, and an attempt were made to investigate the important factors that are effective in the behaviour of bending active structures. An investigation considering the impacts of key areas

including various materials, cross-sections, f/L ratios, and various loading patterns on structures' behaviour was carried out to provide better insights in the appropriate selection for manufacturing and construction of bending active structures.

4.3.1. Behaviour Investigation of Bending Active Structures Constructed by Different Materials

Considerable factor in bending active structures that should be taken into account is related to selection of appropriate materials. Therefore, an essential consideration in bending active structures is to choose materials with a low elastic modulus and high yield stress. In this regard, various samples with different materials were chosen, and their behaviour was investigated. In the following, the materials used in the models were described, and the outcomes were further analysed.

4.3.1.1. Numerical Modelling

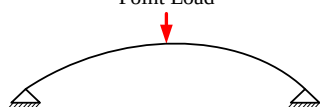
To investigate bending active structures' behaviour with different material specifications, seven circular cross-section samples with various materials, 3 m length, and 25 mm diameter were selected. Various modulus of elasticity was chosen for modelling, as given in Table 4-17, such that a 17 GPa modulus of elasticity was chosen for Model No.1, and in Model No.7, the modulus of elasticity was considered 210 GPa. The selected modulus of elasticity was considered to be close to the modulus of elasticity of materials available in the industry. It should be noted that the behaviour of the chosen materials was considered elastic. One of the bending active structures' main characteristics is strain reversibility and maintaining the elastic behaviour range. Therefore, the stress created in different steps should always stay less than materials' yield stress point. In order to avoid the effect of density and Poisson ratio on the behaviour of materials, it was assumed that all materials had the same specific density of 19 kN/m^3 and Poisson ratio of 0.3 and only their modulus of elasticity was different. These helped to have better comparison on the outcomes.

Table 4-18 presents supports and loading conditions at different stages. In terms of the boundary conditions, both side joints were fully fixed, and the middle point was locked in the z direction.

Table 4-17: Material's specifications.

Model's Number	Density (kN/m ³)	Young's Modulus E (GPa)	Poisson ratio (v)
1	19	17	0.3
2	19	23	0.3
3	19	30	0.3
4	19	40	0.3
5	19	70	0.3
6	19	100	0.3
7	19	210	0.3

Table 4-18: Boundary condition & loading

Steps	Boundary conditions	Loading
1	Right reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Left reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Middle point: $R_z \neq 0$.	Self-Weight applied
2	Applying required joints displacements in X-axis. Final span= 2.6 m 	
3		Applying 100, 200, 400 and 600 N point load in Y-axis to the middle section Point Load 

4.3.1.2. Results

Results after Initial Bending Table 4-19 presents parameters that investigated horizontal reaction force (FR_x), vertical reaction force (FR_y), maximum stress (S_{max}), and minimum stress (S_{min}) created in the models. In the initial bending procedure, different materials did not affect geometrical form-finding shape. As observed from the results, the crown's height (*f*) remained constant in all samples. Therefore, this parameter was not subject to changes in the modulus of elasticity of materials.

Moreover, with an increase in modulus of elasticity, maximum stress and horizontal reactions created in the models increased while the vertical reaction force remained constant. The maximum stress occurred at the top of the samples' crown.

Table 4-19: Result after bending

Model's Number	E (GPa)	RF _x (N)	RF _y (N)	<i>f</i> (mm)	S _{max} (MPa)	S _{min} (MPa)
1	17	392.9	13.26	651.27	148.7	-151.2
2	23	527.3	13.26	651.26	201.1	-204.5
3	30	684.1	13.26	651.28	262.3	-266.7
4	40	908.0	13.26	651.27	349.8	-355.6
5	70	1585.0	13.26	651.25	612.1	-622.2
6	100	2268.0	13.26	651.25	874.4	-888.9
7	210	4753.0	13.26	651.25	1836.0	-1867.0

Changes in the horizontal reactions and maximum stress created in accordance with the modulus of elasticity of the materials are presented in Figure 4-5. In due course, as the modulus of elasticity increased, maximum stress and horizontal reaction forces created in the models also increased. The reason was related to the increased solidity (stiffness) of the structure and greater resistance to deformations. It was found that the greater the modulus of elasticity was, the higher solidity of the structure was. Therefore, resulting in greater resistance to deformations. This resulted in an increase in the horizontal forces of bending application and an increase in the member's stresses. Overall, in case of materials with the same yield strength, lower modulus generates less stresses when the initial form is generated, and the lower modulus material offers more serviceability.

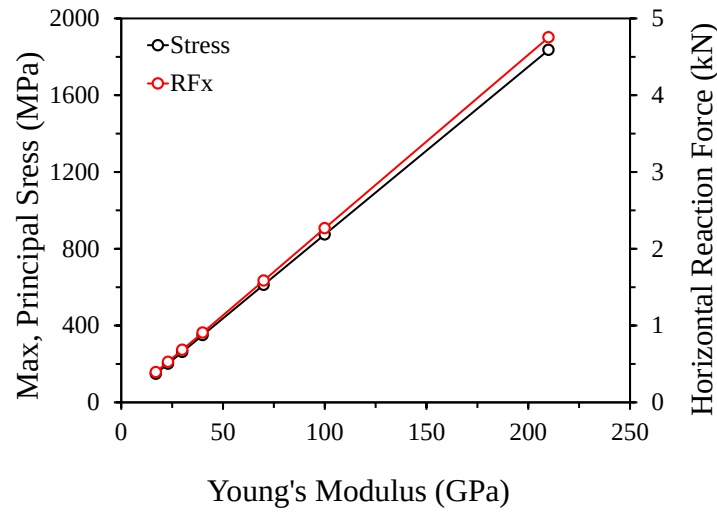


Figure 4-5: Changes in extreme stresses and Young's modulus due to bending

Results after Point Loading

To investigate the structural behaviour under loading, various point loads of 100, 200, 400 and 600 N were applied to the models. Results for the 100 N point loading are presented in Table 4-20 and results for point loads of 200, 400, and 600 N are available in Appendix C-6. Table 4-20 presents the values for arcs crown vertical displacement due to point loading, vertical and horizontal reaction forces, and the maximum stress created. As the unit weight, cross-sections, and length of all models were equal (Table 4-17) the vertical reactions were equal in all models.

Table 4-20: 100N Point Loading

Model's Number	E (GPa)	ΔU (mm)	RF _x (N)	RF _y (N)	S _{max} (MPa)	S _{min} (MPa)
1	17	-3.4	368.8	63.26	141.2	-143.9
2	23	-2.5	632.6	63.26	193.1	-196.7
3	30	-1.9	759.9	63.26	254.0	-258.6
4	40	-1.4	983.9	63.26	341.2	-347.2
5	70	-0.8	1655.7	63.26	603.1	-613.5
6	100	-0.6	2327.5	63.26	865.2	-880.0
7	210	-0.3	4790.8	63.26	1827.0	-1858.0

Figure 4-6 plots horizontal reaction changes in different models. With the increase in point loading, horizontal reaction forces increased at the supports. These changes were almost the same in all models. Therefore, changes in the materials did not affect vertical reaction forces.

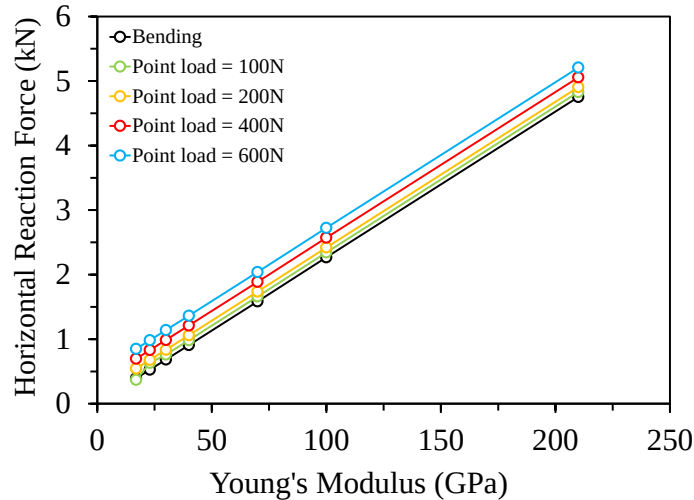


Figure 4-6: Reaction force (RFx) vs Young's modulus (for different point loads)

Figure 4-7 illustrates maximum stress created in the models related to the modulus of elasticity of materials. According to the results captured, the maximum stress in models grew with increasing modulus of elasticity. By applying a 400 N point loads, the maximum stress in the model with 17 GPa was equal to 134.3 MPa and, in a model with a modulus of elasticity of 30 GPa, recorded 240.1 MPa. Increasing the samples' stiffness led the samples to approach the yield point via less stress. Thereupon, as it was out of the elastic range permanent deformations would occurred in the samples. It was also observed, the maximum stress in the initial bending step was more significant than the stresses created after the point loading. When the point load increased, the arcs crown moved downwards which resulted in the stress redistribution, and the maximum stress relocated from the crown to the sides of the models. In other words, adding loads bends the crown of the structure closer to its original unbent shape and therefore reduces stress.

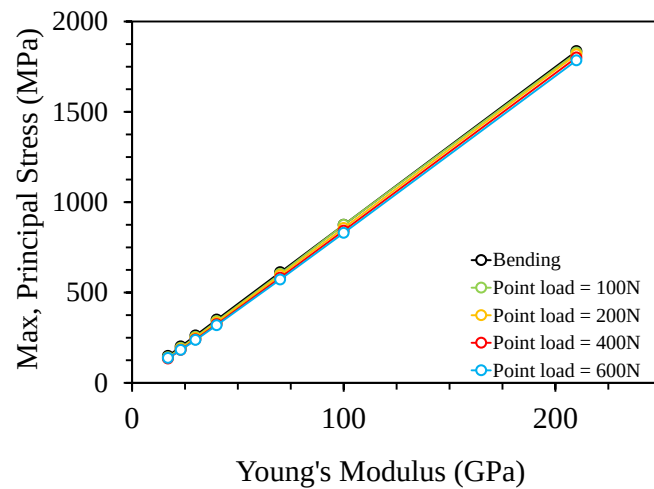


Figure 4-7: Extreme stresses vs Young's modulus (for different point loads)

Figure 4-8 presents the arc's crown displacement in different models under various point loading. The pattern showed that increase in the modulus of elasticity led to decrease in the arc's crown displacement. In models with a modulus of elasticity of 17 GPa, by applying 200 N point load, the arc moved downwards 7.1 mm. However, in samples with a modulus of elasticity of 40 GPa, a downwards displacement of 2.9 mm was recorded. Increasing stiffness in the models affected the displacement. Therefore, with increasing modulus of elasticity, the structure's stiffness increased which causes less displacement during loading.

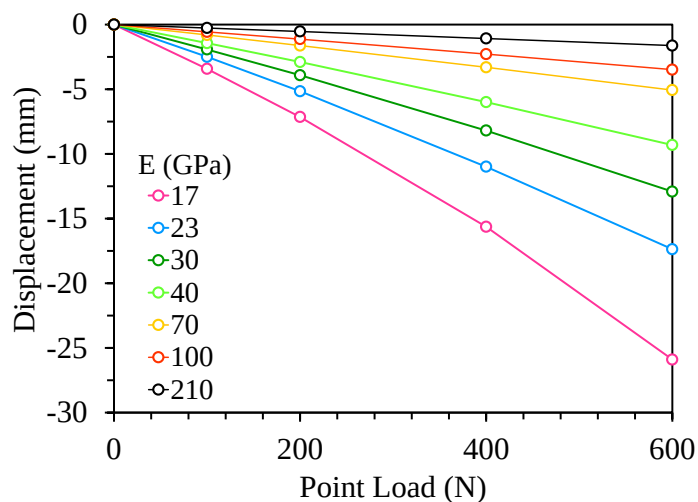


Figure 4-8: Crown's displacement in vertical direction vs Point load

4.3.1.3. Conclusion

Higher modulus of elasticity increased rigidity in the materials. This increase in stiffness was observed in both, the force required for initial bending and the displacement under loading. On the other hand, with increasing stiffness in samples, the stress created increased and was brought closer to the materials yield stress point. Exceeding yield stress point causes permanent (plastic) deformation, which contradicts bending active structures' initial definitions.

For this reason, materials with low modulus of elasticity and high yield stress should be used in the construction of bending active structures to avoid reaching yield stress point during initial bending and external loading to prevent permanent deformations. Although external loading could reduce the stress created at the crown, this stress will be redistributed to the other sections. Therefore, the deformation due to external loading must be thoroughly monitored and controlled in such structures as it could highly influence the performance of the structure.

4.3.2. Behaviour Investigation of Bending Active Structures with Different Cross-sections

An important consideration in bending active constructions is choosing appropriate cross-sections. To review the effect of various cross-sectional area's impact on bending active behaviour, models with different cross-sectional areas were investigated. In order to compare the outcomes, the cross-sectional areas were kept in constant.

4.3.2.1. Numerical Modelling

To study the effect of cross-sections on bending active structure's behaviour, samples with three different sections in four shapes of square, circle, horizontal rectangle and vertical rectangle with 3 m length were chosen. Samples were classified into two groups, in which the cross-sectional area of the second group was considered to be twice the area of the first group. GFRP samples with 30 GPa modulus of elasticity, density of 19 kN/m^3 and 0.3 Poisson ratio were used. To have a clear view of bending behaviour, samples were subjected to 8 displacements from 0.1 m to 0.8 m. Table 4-21

presents supports and loading conditions in different steps, and models' characteristics are presented in Table 4-22.

Table 4-21: Boundary condition & displacements

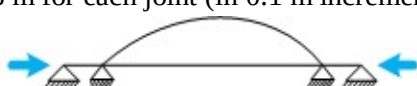
Steps	Boundary Condition	Loading
1	Right reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Left reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Middle point: $R_z \neq 0$.	Self-weight
2	Joints displacements in the X-axis from 0.1 m to 0.8 m for each joint (in 0.1 m increments) 	

Table 4-22: Models' characteristics

Model Number	Section Shape	Dimensions (mm)	Optimised mesh size (mm)	Schematic
1	Circle	Radius 6.25	5	
2		Radius 12.5	10	
3	Square	10.5×10.5	5	
4		22×22	10	
5	Horizontal Rectangle	22.5×5	2.5	
6		49×10	5	
7	Vertical Rectangle	5×22.5	2.5	
8		10×49	10	

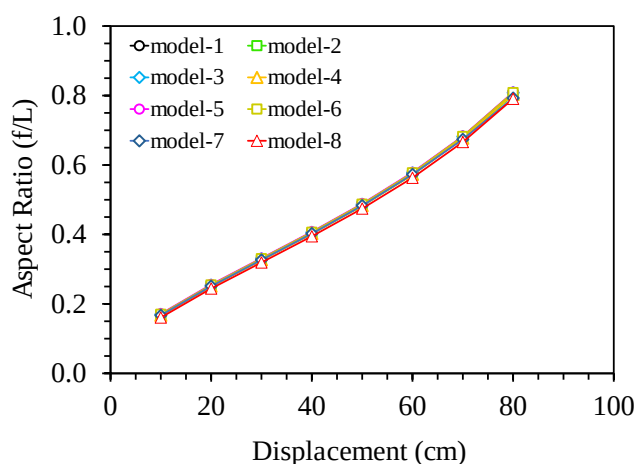
4.3.2.2. Results

Computations related to the f/L ratio

Initial bending was created by joints' displacement. As joints became closer, the height of the arcs crown increased, and its secondary spans became smaller; thus, the height to span (f/L) ratio decreased. With displacing joints 0.3 m, a 0.33 f/L ratio was created, and a 0.6 m displacement created a 0.58 f/L ratio. The test outcomes indicated that the cross-sectional shape had a minor effect on the f/L ratio. Table 4-23 presents aspect ratios for eight models.

Table 4-23: Aspect ratios in different supports displacement for eight models

Displacement (m)	f/L							
	Model's Number							
	1	2	3	4	5	6	7	8
0.1	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16
0.2	0.25	0.25	0.25	0.25	0.26	0.25	0.25	0.24
0.3	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.32
0.4	0.41	0.40	0.41	0.40	0.41	0.41	0.40	0.39
0.5	0.49	0.48	0.49	0.48	0.49	0.49	0.48	0.47
0.6	0.58	0.57	0.58	0.57	0.58	0.58	0.57	0.56
0.7	0.68	0.68	0.68	0.68	0.68	0.68	0.67	0.67
0.8	0.81	0.80	0.81	0.80	0.81	0.81	0.79	0.79

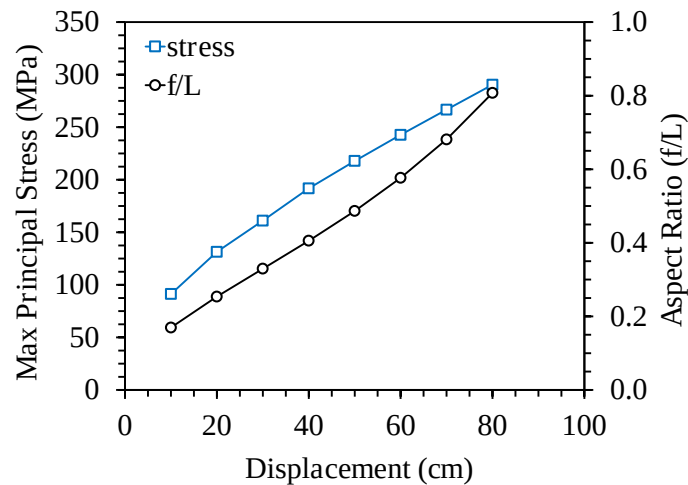
**Figure 4-9: Models' aspect ratios**

Computations of Maximum Stress

Table 4-24 presents maximum stress created due to supports displacement. The maximum stress created in samples increased as the secondary span shrunk. It can be illustrated, that the maximum stress created in models was different in terms of various sections. For example, applying 0.3 m joints displacement created the maximum stress of 161.1 MPa in Model No.1 and 334.7 MPa in Model No.2. This difference in maximum stress created could be observed in all models. Figure 4-10 illustrates the maximum stress created and aspect ratio of Model No.1, and figures for other models are available in Appendix C-7.

Table 4-24: Maximum principal stresses

Displacement (m)	Smax (MPa)							
	Model's Number							
	1	2	3	4	5	6	7	8
0.1	91.25	184.40	70.85	144.20	34.72	68.08	159.60	328.20
0.2	131.40	267.90	102.00	209.40	49.49	98.13	231.80	485.00
0.3	161.10	334.70	127.00	261.60	61.28	122.20	289.50	610.60
0.4	191.80	393.50	148.90	307.60	71.64	143.50	340.50	721.30
0.5	217.90	447.80	169.20	350.10	80.20	163.10	387.50	823.40
0.6	242.70	499.40	188.40	390.40	90.27	181.80	432.20	920.00
0.7	266.70	549.40	207.10	429.60	99.06	200.00	531.80	1015.00
0.8	290.40	598.60	225.50	468.30	107.70	217.90	592.60	1108.00

**Figure 4-10: Maximum principal stress & Aspect ratio Vs various support point displacement, Model No.1**

Horizontal reaction forces as a result of joints displacement are illustrated in Figure 4-11 and Figure 4-12 for both groups. The results demonstrated that the increase in displacement correlated with increased reaction forces in all models. The highest horizontal reaction was created in the samples with vertical rectangle cross-section, followed by the square, circle and lastly the horizontal rectangle cross-section. The horizontal reaction forces created in samples with square and circular cross-sections

were very similar to each other. Accordingly, it can be concluded that with increasing the moment of inertia of the cross section, the stresses and horizontal reactions increased. Except vertical rectangular models, the horizontal reactions had no significant change with increasing the displacement. Also, in Model No.8 as displacement increased the model was distorted and the stress and horizontal reactions were unrealistically changed.

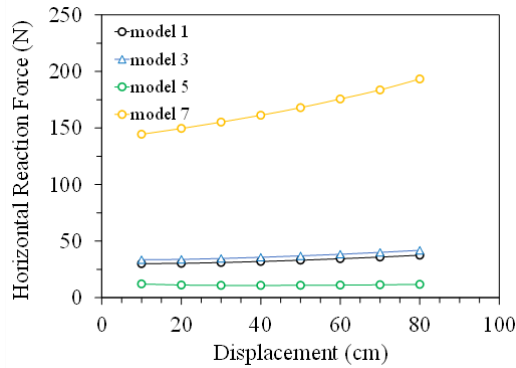


Figure 4-11: Horizontal reaction forces in different displacements (models 1, 3, 5 & 7)

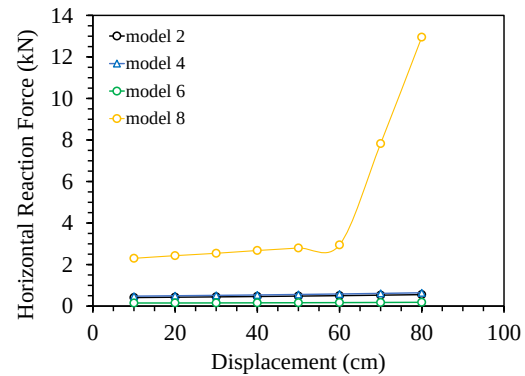


Figure 4-12: Horizontal reaction forces in different displacements (models 2, 4, 6 & 8)

The maximum stress created in samples with the same cross-sectional area is presented in Figure 4-13 and Figure 4-14. During displacing, as joints moved closer toward each other the stress created in the models increased. It can be illustrated that square, circle and horizontal rectangular cross-sections had the same trend in maximum stress creation at various displacements. The horizontal rectangular cross-section had the lowest stress during bending. On the other hand, the vertical rectangular had the highest stress between models. Vertical and horizontal rectangular cross-sections were considerable examples as they have the same cross-section, yet, the side that bending created was different, made a significant difference in stress created. It can be concluded that in addition to the cross-section shape and size, the orientation and angle of bending applied were fundamental and should also be taken into consideration. Also, a comparison of maximum stress in both groups showed that the maximum stress in models with a larger cross-sectional area was greater. Therefore, according to the

explanations provided, the choice of cross-section is an effective factor to meet the requirements in bending active design.

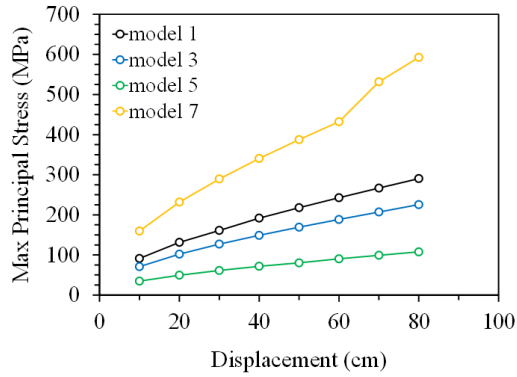


Figure 4-13: Maximum principal stress created due to displacements (Models 1, 3, 5 & 7)

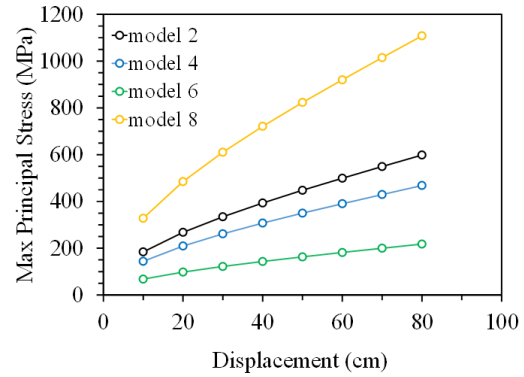


Figure 4-14: Maximum principal stress created due to displacements (Models 2, 4, 6 & 8)

Figure 4-15 and Figure 4-16 present the deformations and stress distributions of Model No.1. As illustrated, maximum stress occurred at the top of the crown, precisely in the middle of the model.

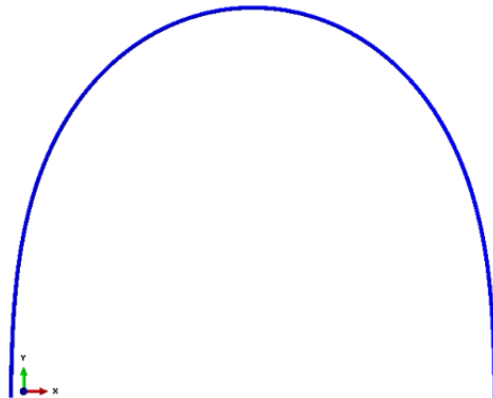


Figure 4-15: Model No. 1 deformation

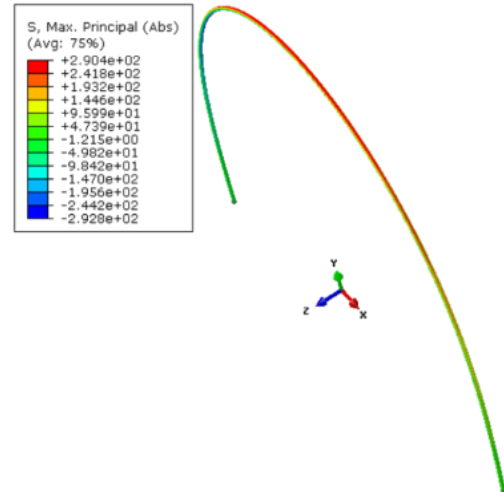


Figure 4-16: Model No. 1 Stress distribution

4.3.2.3. Conclusion

From investigating the effect of various cross-sections on bending active models, it can be concluded that the geometric shape of the cross-sections had a significant impact on the stress created in the structure while it had a negligible effect on f/L ratios. Apart

from the cross-sectional shape and size, the angle of the component that bending applied greatly impact the stress creation and distribution. For instance, Model No.6 and No.8 had same rectangle cross-sections, while due to the angle that bending was applied, the results were remarkably varied. Increasing stress in the structure causes the initial stress to be closer to the yield stress point and, as a result, disrupts the behaviour of bending active structures. Therefore, by passing the yield stress point, the strain created in the structure reach a plastic strain, disturbing the main function of these structures, which highlights the importance of appropriate geometry in the design of bending active structures.

4.3.3. Behaviour Investigation of Bending Active Structures with Different f/L ratio

Bending active structures are built and used in different geometries with the various ratio of the height to the secondary length (f/L), which has a direct impact on the structure's performance. Therefore, it is essential to study the effect of various f/L ratios on structures' behaviour. In this section, the structural behaviour of bending active models such as stresses and deformations with the same cross-sectional area and different f/L ratios was investigated.

4.3.3.1. Numerical Modelling

To investigate the behaviour of bending active models with various f/L ratios, circular cross-section samples with 25 mm diameter and initial lengths of 3, 5, 7, 10, 12 and 15 m were chosen to create various f/L ratios by moving the joints and reaching a secondary span of 2.6 m. Then, the structural behaviour under point loading application was investigated.

GFRP material with 30 GPa modulus of elasticity, 19 kN/m^3 density and 0.3 Poisson ratio was used for numerical modelling in all models. Table 4-25 illustrates the supports and loading conditions, and Table 4-26 presents the displacements required for each support to reach the secondary span of 2.6 m and the optimal mesh size used in the modelling.

Table 4-25: Boundary condition & situation of loading in each step

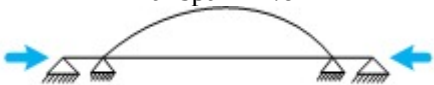
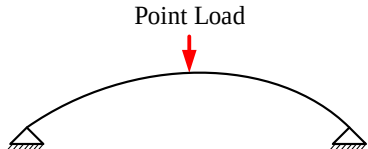
steps	Boundary Condition	Loading
1	Right reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Left reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Middle point: $R_z \neq 0$.	Self-Weight applied
2	Applying displacement in the X -axis. Final span= 2.6 m 	
3		Applying 100, 200, 400, and 600 N point load in the Y -axis to the middle of the model 

Table 4-26: Displacement in each support and optimised mesh size

Initial Span (m)	Displacement point in Longitudinal direction (m)	Optimised Mesh size (mm)
3	0.2	10
5	1.2	10
7	2.2	15
1	3.7	20
12	4.7	20
15	6.2	20

4.3.3.2. Results

Results after Initial Bending

Model No.1 with 3 m length reached the secondary span of 2.6 m after initial bending, and the height of the arc's peak (f) recorded 651.3 mm as presented in Table 4-27. Horizontal and vertical reaction forces created due to bending were 684.10 N and 13.26 N, and the maximum stress created in the model was 262.3 MPa. With the increase in length, the height of the model increased respectively, and in Model No.2 with 5 m length, it reached 1828.2 mm. This trend continued in all models, and f reached 5844.5 mm in Model No. 6 with 15 m length. The horizontal forces created in the models were dependent on the force required to displace the joints and attain a

secondary span of 2.6 m. The horizontal reaction forces for 3 m model recorded 684.10 N, and 43.80 N for the 15 m model. Results indicated a reduction in the force applied for displacement in longer models which have a direct connection to models' slenderness. In this experiment radius of gyration was equal in all models. As observed with increasing the length, horizontal reaction decreased, and less force was needed to apply the bend in sections with high slenderness. The maximum stress increased with the increase in the sample's length, up to $0.7 f/L$ ratio. In the model with a $0.25 f/L$ ratio, the stress created was equal to 262.3 MPa, and it increased to 330.6 MPa in the model with $0.7 f/L$ ratio. Continuing this, it was seen that with increasing the model's length, the stress decreased and reached 153.3 MPa in a model with $2.25 f/L$ ratio. In Figure 4-17, the final arcs shape is presented after applying the supports displacement. More details, such as support displacement and initial bending creation of models are presented in Table 4-27.

Table 4-27: Result after initial bending

Models	Length (m)	f (mm)	L (m)	f/L	RFx (N)	RFy (N)	S_{max} (MPa)	S_{min} (MPa)
1	3	651.3	2.6	0.25	684.10	13.26	262.3	-266.7
2	5	1828.2	2.6	0.70	309.50	22.10	330.6	-334.2
3	7	2733.0	2.6	1.05	193.40	30.94	290.4	-293.1
4	10	3977.7	2.6	1.53	114.60	44.20	234.8	-236.6
5	12	4761.4	2.6	1.83	79.58	53.04	200.4	-201.7
6	15	5844.5	2.6	2.25	43.80	65.50	153.3	-154.1

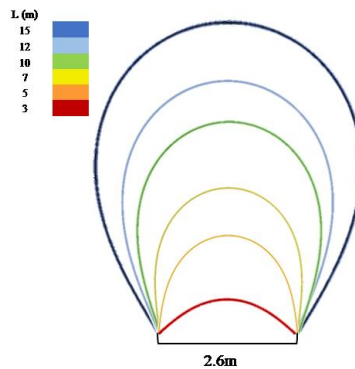


Figure 4-17: Deformation of 6 models after Step 2 (bending active)

Maximum stress variation and horizontal reaction forces for samples with various f/L ratios are shown in Figure 4-18. Maximum stress created in the models varied based on f/L ratios. At first, with the increase in f/L ratio maximum stress in models increased. However, from Model No. 3 with a f/L ratio of 1.05 where the angle of deflection passed 90 degrees, as the ratio increased a reduction in maximum stress was experienced. This could be seen in the geometrical shape of the samples. According to the final shape of the structures (shown in Figure 4-17), at lower f/L ratios, the arc's geometrical shape was closer to the dome arc shape, however with the increase in ratio, the curves became horseshoe shaped, and in such cases, less stress was created owing to bend the structure. Samples with longer length resulted in horseshoe shape due to low rigidity, and less horizontal force was required to apply the initial bending. Thus, less horizontal reaction force was created at the supports. Therefore, with increasing the f/L ratio, horizontal reaction forces decreased.

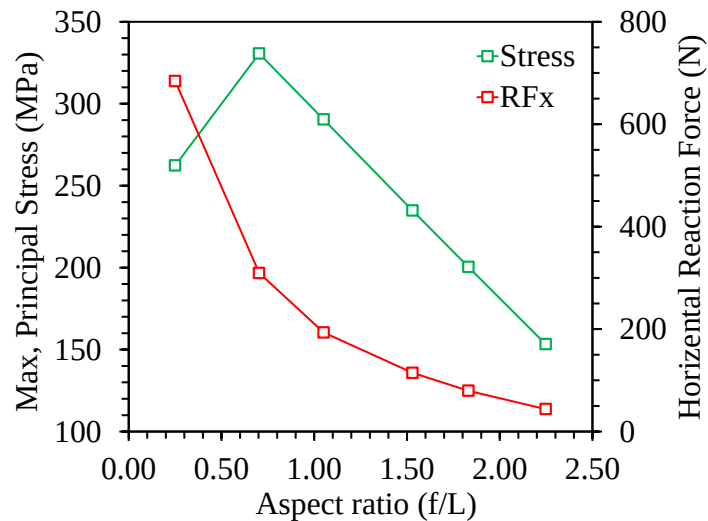


Figure 4-18: Changes in maximum stresses and horizontal reaction forces vs aspect ratio

Results after Point Loading

To investigate load bearing behaviour, samples were subjected to point loading by applying 100, 200, 400 and 600 N loads. Results for 100 N point load are presented in Table 4-28. Additionally, results for point loads of 200, 400 and 600 N are available in

Appendix C-8. With the increase in point load, arc's displacement in all models increased. In the Model No.2, displacement under 200 N point load recorded 20.41 mm and 71.43 mm at 600 N point load. Also, models' length had a direct effect on arc's displacement under loading. This could be illustrated that under 100 N point load, 1.90 mm displacement created in the Model No.1 and increased to 85.14 mm in the Model No.4. Furthermore, in the Model No.6 it reached to 481.78 mm. The maximum stress creation in the models did not follow the same trend in all models, so that, the maximum stress firstly increased up to Model No. 2 and then with increasing length maximum stress created reduced. At 200 N point load, maximum stress value in the Model No.1 recorded 254.0 MPa and in the Model No. 2 obtained 316.6 MPa. Decreasing continued in a way that it reached 150.8 MPa for the Model No.6.

Table 4-28: Results after applying 100N point load

Length (m)	Δu (mm)	RFx left (N)	RFy left (N)	S_{max} (MPa)	S_{min} (MPa)
3	-1.90	759.9	63.26	254.0	-258.6
5	-9.84	331.4	72.1	316.6	-320.1
7	-27.82	204.3	80.94	272.5	-275.1
10	-85.14	117.8	94.18	214.0	-215.6
12	-169.64	79.1	103	180.6	-181.8
15	-481.78	37.88	115.5	150.8	-151.7

Maximum stresses created and the geometrical shapes of models differ at variant f/L ratios. This means, when the f/L ratio was within 0.7, the maximum stress grew. Figure 4-19 illustrates variations in maximum stresses created in samples with different ratios under point loading. The stresses created under 100 N point loading was close to the initial bending values. However, with increasing point loading, the stress changed with differing f/L ratios, which meant that by increasing the applied load in the f/L ratios of less than 1, the maximum stresses created in the models increased. While in the f/L ratios of more than 1, the maximum stresses created reduced due to the deformations caused by loading in the models.

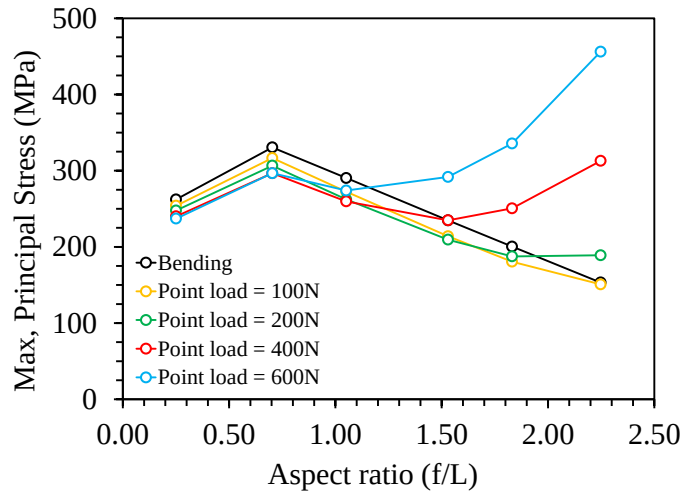


Figure 4-19: Maximum stresses vs f/L (for different point loads)

Variations in horizontal reaction forces did not follow the same trend with increasing f/L ratios, as shown in Figure 4-20. In Model No.1, the horizontal reaction forces increased with an increase in the point loading. The horizontal reaction forces rose with increasing point loading. Meanwhile by increasing the f/L ratio, horizontal reactions rate subtracted. In the $f/L = 1.53$ ratio, the horizontal reaction forces for all models were almost identical under various point loading. Further into the experiments, as the point load increased, the horizontal reactions decreased due to large deformations in models with high f/L ratios.

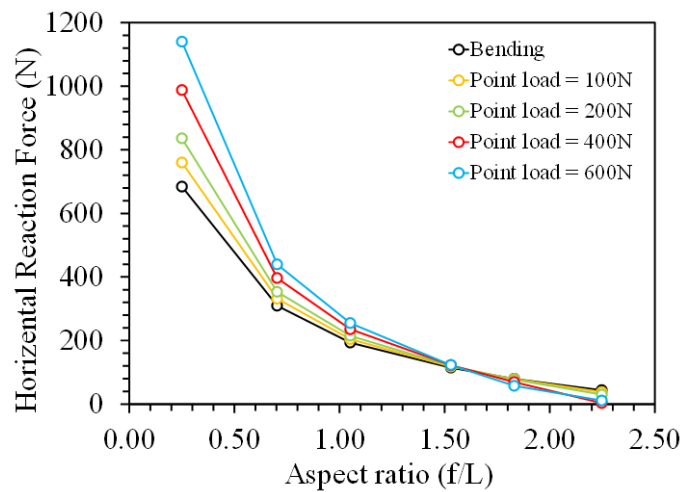


Figure 4-20: Horizontal reaction forces (RFx) vs aspect ratio

In the following, a few examples of deformations in the initial shape and under different loading are presented in Figure 4-21. It was observed that by increasing the point load, displacement of the arc's crown in models increased. Also, in models with higher ratios, these displacements caused large deformations on the models. In fact, in models with a f/L ratio of more than 1.53 (lengths greater than 10 m) large deformation occurred which could lead to instability or a collapse.

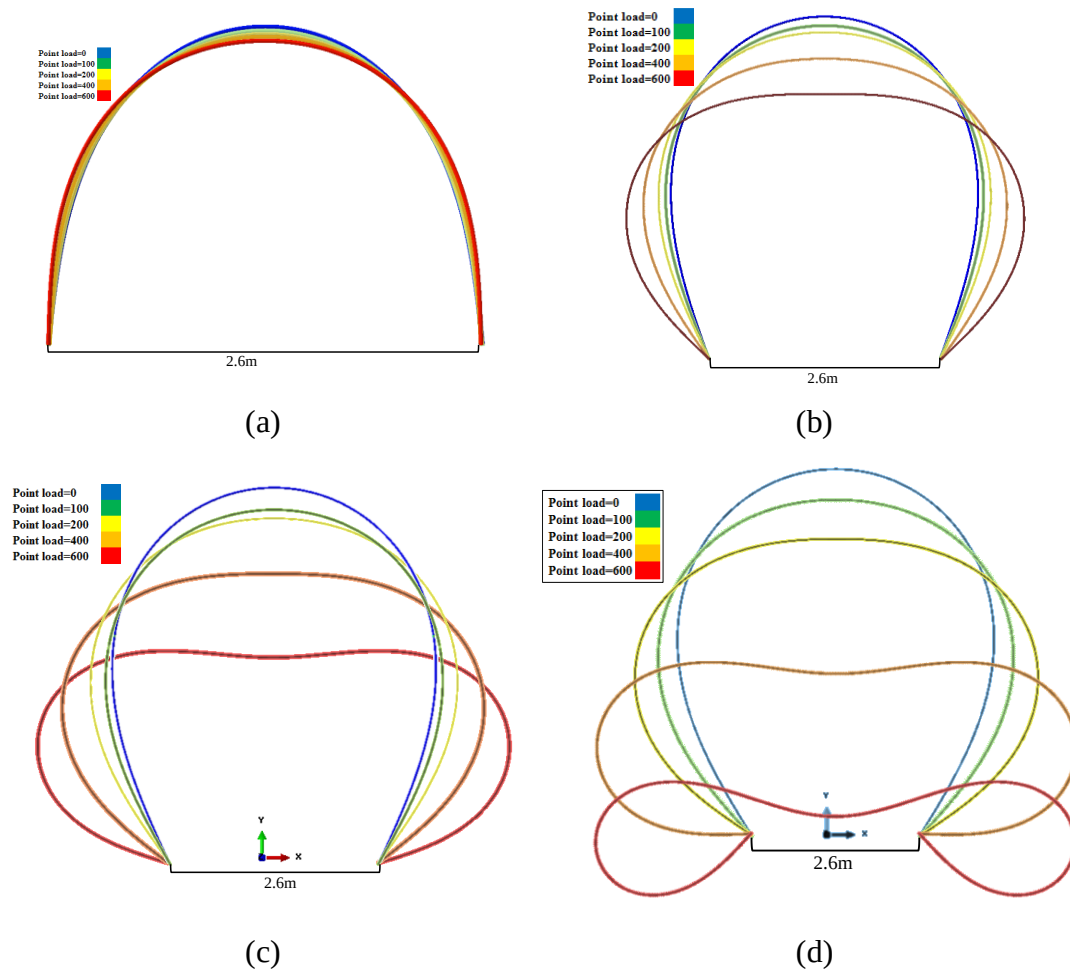


Figure 4-21: Maximum principal stress (a: 5m, b: 10m, c: 12m& d: 15 m)

4.3.3.3. Conclusion

According to the results obtained, it was observed that the f/L ratio was an essential factor in bending active structures and different f/L ratios created various geometries.

The f/L ratio was dependent on the samples' slenderness. In other words, the model's slenderness and geometry had a direct effect on structural behaviour. At low f/L ratios (up to about 0.7), with the increase of the ratio, the initial stresses created in the structure increased. However, in the sample with f/L ratio greater than 0.7, less initial stresses were created during bending. It was further observed that greater the f/L ratio was, the greater deformations occurred. Therefore, the f/L ratio up to 0.7 is recommended during the design stage.

4.3.4. Behaviour Investigation of Bending Active Structures with Differing Lengths and a Constant f/L ratio

Bending active structures have the capability of being built in various sizes. Models with various length and fixed f/L ratios are one of the areas which require an investigation to have a clear view of ratio effect on bending active structures behaviour.

Conducting numerical modelling of structures with the specifications mentioned is helpful in comprehending the behaviour of structures with various lengths. Based on the findings in Section 4.3.3, models with the f/L ratios of between 0.25 and 0.7 had a better performance under bending and loading. Thus, this section considers the behaviour of models with different lengths at a fixed f/L ratio of 0.3 for all models.

4.3.4.1. Numerical Modelling

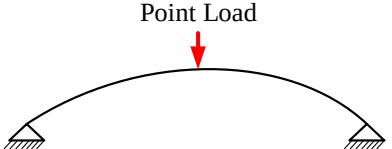
To investigate desired configurations, circular cross-sectional samples with 25 mm diameter and 3, 5, 7, 10, and 12 m lengths with the fixed 0.3 f/L ratio were used for numerical modelling. Then the behaviour of models during the initial bending and point loading was examined. Material assigned for models in numerical modelling was GFRP with 30 GPa modulus of elasticity, density of $19kN/m^3$, and a 0.3 Poisson coefficient.

Table 4-29 shows the displacements required for each joint and the optimized mesh size used in modelling. Joints and loading conditions in different steps are shown in Table 4-30.

Table 4-29: Displacement in each support and optimized mesh size

Initial Span (m)	Displacement in Longitudinal direction (m)	Optimised Mesh Size (mm)
3	0.265	10
5	0.435	10
7	0.605	15
10	0.860	20
12	1.035	20

Table 4-30: Boundary condition & situation of loading in each step

Step	Boundary Condition	Loading
1	Right reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Left reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Middle point: $R_z \neq 0$.	Self-weight applied
2	Applying required displacements in the X-axis to form the desired curve with $f/L = 0.3$. 	
3		Applying 100, 200, 400, and 600 N point load in the Y-axis to the middle section 

4.3.4.2. Results

Results after Bending

Results from investigating the various models with an equal f/L ratio are presented in Table 4-31. As the model's length increased, the reaction forces and maximum stresses created in models decreased. This was due to the sample's slenderness which, with the increase in length, the slenderness in models increased, and therefore, the model's stiffness reduced.

Table 4-31: Results after step 2 (bending)

Model	Length (m)	f (mm)	L (m)	f/L	RF_x (N)	RF_y (N)	S_{max} (MPa)	S_{min} (MPa)
1	3	740.7	2.47	0.30	700.20	13.26	305.9	-310.8
2	5	1237.2	4.13	0.30	266.70	22.10	184.4	-186.2
3	7	1733.9	5.79	0.30	164.00	30.94	136.2	-137.3
4	10	2479.7	8.28	0.30	111.60	44.20	99.64	-100.3
5	12	2984.5	9.93	0.30	94.66	53.04	83.59	-84.13

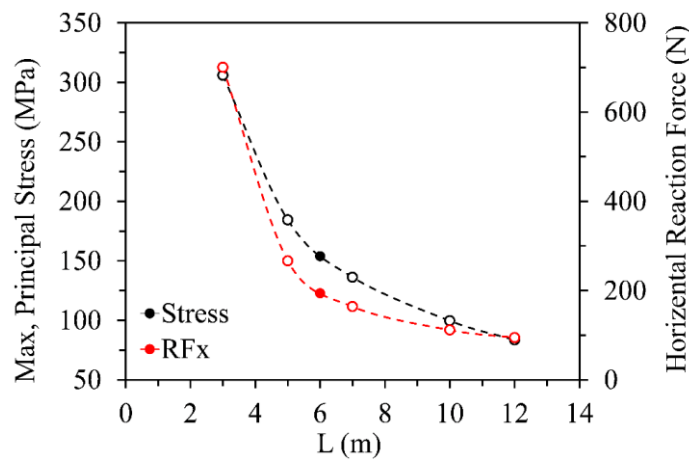


Figure 4-22: Maximum stresses & horizontal reaction force vs rebar length

Results after Point Loading

To study the structural behaviour of desired bending active configurations under loading, point loads of 100, 200, 400, and 600 N were applied to the models. Results for 100 N point load are presented in Table 4-32, also outcomes for the rest of the tests under loading of 200, 400, and 600 N are available in Appendix C-9.

Table 4-32: Results after applying 100N point load

Model	Rebar length (m)	ΔU (mm)	RF_x (N)	RF_y (N)	S_{max} (MPa)	S_{min} (MPa)
1	3	-1.90	762.8	63.26	297.4	-302.5
2	5	-8.78	329.9	72.1	172.9	-175.0
3	7	-22.94	227.4	80.94	124.5	-125.8
4	10	-67.65	175.1	94.2	90.2	-91.1
5	12	-137.87	157.9	103	78.3	-79.1

Horizontal reaction forces created in the models with different lengths are presented in Figure 4-23. With the increase in the model's length, the horizontal reactions in models decreased due to the reduction in the model's stiffness. Models' behaviour under loading of up to 200 N was in the acceptable range, however, from the 400 N load application, unexpected results were obtained from some models. With applying 400 N point load, the Model No.5 failed to carry the load and due to unexpected behaviour the simulation was not able to continue. The same results were recorded for Model No.4 and 5 under 600 N point loading.

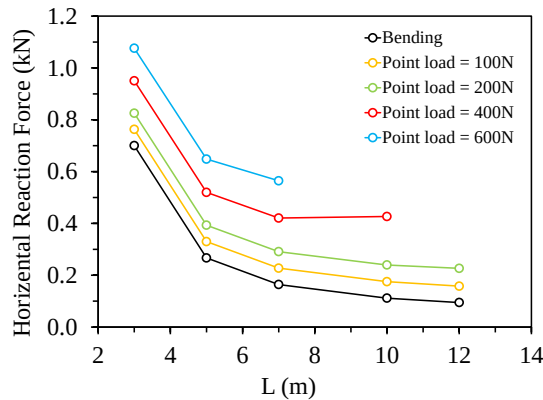


Figure 4-23: Reaction force (RFx) vs model's length (under various point loading)

With the increment in the model's length, the stress created in models decreased, as illustrated in Figure 4-24. A slight change was indicated in stresses after applying 100 and 200 N point loads. However, due to the large deformation in Model No.4 and 5, under point loading, the analysis was not performed as the models were not able to carry the load.

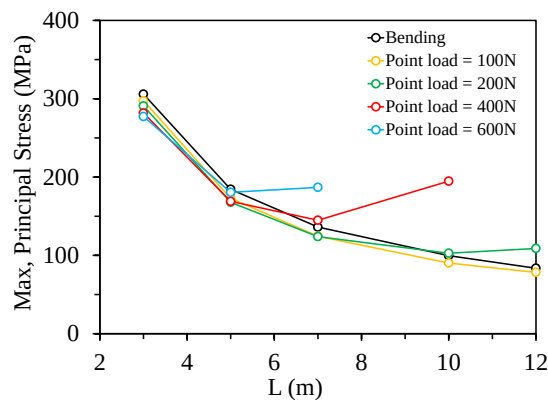


Figure 4-24: Maximum stresses vs rebar length (under different point loads)

Figure 4-25 illustrates vertical displacement at the top of the models under various loading. Loading had a direct effect on the arc's displacements. The displacements created in the models increased with the increment in models' dimensions. The numerical modelling was not convergent because of the significant deformations created under larger loading in Model No.4 and 5.

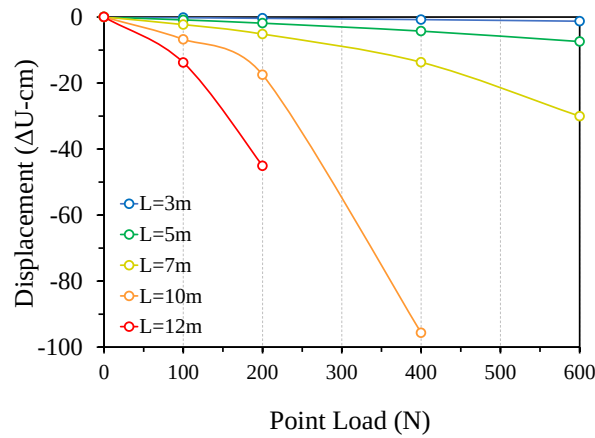


Figure 4-25: Top point's displacement in vertical direction vs point load (for different rebar's length)

4.3.4.3. Conclusion

Bending active theory can be used practically in lightweight structure, particularly given that such structures can be manufactured in different sizes. To design a safe structure, it is necessary to consider all aspects and potential configurations. Thus, studying the behaviour of such models with various lengths and the same f/L ratio was highlighted. With the increase in length of members with the same cross-sectional area, stiffness decreased, and as a result, the stress and horizontal reactions created due to bending reduced. Also, in the point loading application, the displacement was directly related to the members' length, so that displacement was more significant in models with longer lengths. The displacement is an important factor in structures, depending on their type of use. Therefore, if the displacements were greater than designed allowance, the structure may not function properly and could cause unexpected behaviour or structural failure.

4.3.5. Behaviour Investigation of Bending Active Structures under Varying Loading

4.3.5.1. Introduction

Due to the usability of bending active structures for various structural purposes, load-bearing capacity is an important area needed to be investigated. As these structures encounter considerable stresses during initial bending, it is necessary to control the stresses and deformations created in the structure at all stages. This helps to retain the key factors in such structures, for example, elastic behaviour and reversibility. Therefore, in this section, an attempt was made to examine such structures' behaviour under various types of external loading.

4.3.5.2. Numerical Modelling

To investigate bending active structures' behaviour under various loading configurations, a 3 m GFRP rod with a 25 mm diameter was chosen. After the initial bending applied, six different loading patterns were applied to the models. GFRP material used in numerical modelling with elastic modulus of 30 GPa, 19 kN/m^3 density, and 0.3 Poisson coefficient in all models. Table 4-33 illustrates the support and loading condition in all steps.

Table 4-33: Boundary condition & situation of loading in each step

Step	Boundary Condition	Loading
1	Right reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Left reaction: $R_x \neq 0, R_y \neq 0, M = 0$. Middle point: $R_z \neq 0$.	Self-Weight
2	Applying required joint displacements in the X -axis. Final span=2.6 m 	
3	Loadings involve: - Applying three forms of loading perpendicular to the structure's axis with a 1.6 kN/m intensity. - Applying extended and point loadings of 2.3 kN in the vertical axis. - The sum of the loads are the same in all models.	

To examine load-bearing behaviour, six prevalent patterns of external loading were chosen to apply to the models. Loading configurations are presented in Figure 4-26.

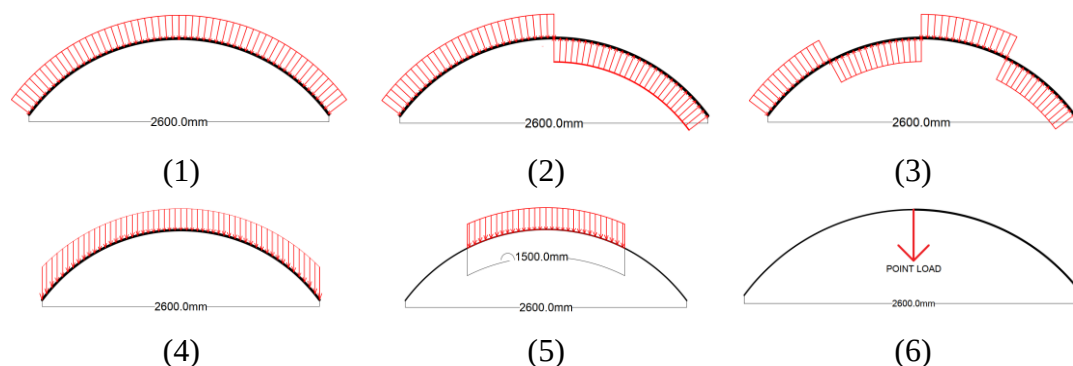


Figure 4-26: Loading patterns

4.3.5.3. Results

After Bending

Stresses created during initial bending, reaction forces and displacements in the models are presented in Table 4-34, which was equal in all models. Accordingly, with 0.2 m displacement in each joint, models with 0.25 f/L ratio were created. The horizontal and vertical reactions created due to bending were 684.1 N and 13.26 N, respectively, and the maximum stress created was equal to 262.3 MPa.

Table 4-34: Result after step 2 (bending)

$f(\text{mm})$	$L \text{ (m)}$	f/L	$RF_x \text{ (N)}$	$RF_y \text{ (N)}$	$S_{\text{max}} \text{ (MPa)}$	$S_{\text{min}} \text{ (MPa)}$
651.3	2.6	0.25	684.10	13.26	262.3	-266.7

After External Loadings

A summary of results under various point loading application are presented in Table 4-35.

Table 4-35: Results after applying different loading (step number 3)

Loading pattern	ΔU (mm)	RF_x Left (N)	RF_x Right (N)	RF_y Left (N)	RF_y Right (N)	S_{max} (MPa)	S_{min} (MPa)
1	19.4	2223.0	-2223.0	2019	2019	330.5	-346.5
2	-151.5	48.8	-1594.0	984	-704	482.8	-490.6
3	-1.7	294.4	-1076.0	426	-398	318.2	-323.4
4	7.0	1452.0	-1452.0	1018	1018	287.8	-297.8
5	-21.0	2162.0	-2162.0	1125	1125	214.6	-225.6
6	-87.6	2491.0	-2491.0	1163	1163	318.8	-332.3

In loading pattern 1, 1600 N/m distributed load was applied perpendicularly to the upper web of the model. The geometry deformation under loading is presented in Figure 4-27, and stress distribution is presented in Figure 4-28. It can be illustrated that the model's arc moved 19.4 mm upward due to loading. Since the loading pattern was symmetrical, the reaction forces created at both joints were equal to 2223 N. Considering that the middle part of the model, under the influence of the applied force, moved vertically in the positive vertical direction, the maximum and minimum stresses created in the model were obtained 330.5 MPa and -346.5 MPa, respectively.

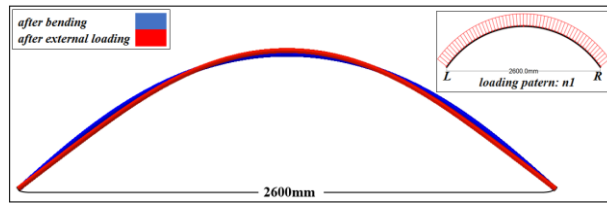


Figure 4-27: Model's Deformation under loading- Pattern 1

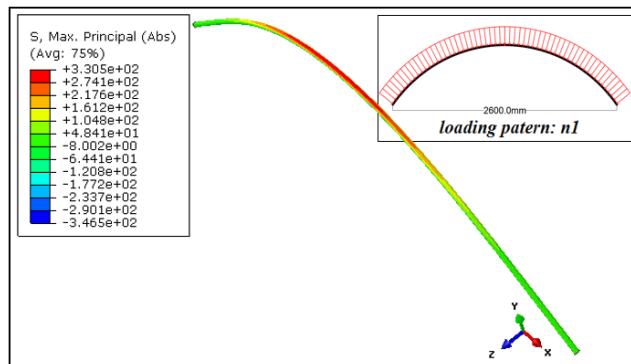


Figure 4-28: Stress distribution contour - Pattern 1

In loading pattern 2, two equal pressure distributed loads were applied to the structure's left and right sides in opposite directions. Geometrical deformation and stress distribution are presented in Figure 4-29 and Figure 4-30. During loading, the arc's crown moved 0.15 m downwards in the vertical direction. Since loading was not symmetrical with respect to the model's longitudinal centre, uneven reaction forces were created at joints. The horizontal reaction force at the right joint exceeded by approximately 1500 N. Likewise, the vertical support's reactions were not equal and corresponded to the load direction applied. Before applying external loading, the maximum and minimum stresses generated from the initial bending phase, occurred at the middle of the sample. However, after applying loading pattern 2, the position of the maximum and minimum stresses shifted to the right side of sample, which can be found in detail in Figure 4-30.

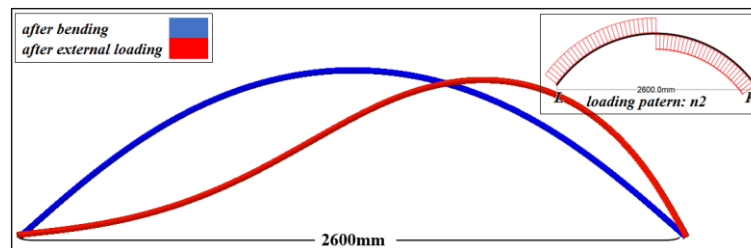


Figure 4-29: Model's Deformation under loading- Pattern 2

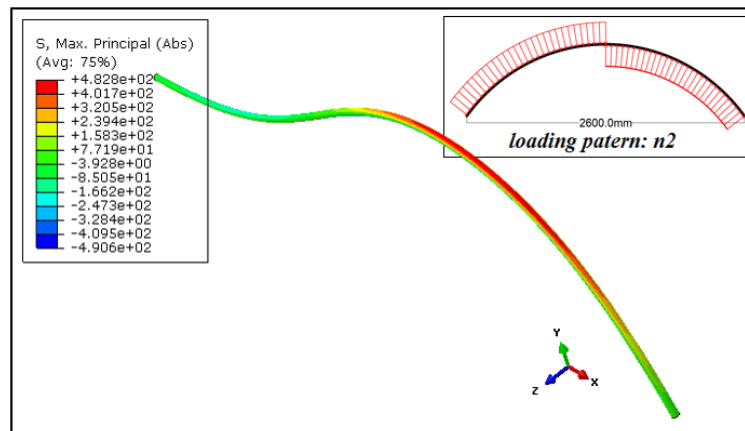


Figure 4-30: Stress distribution contour - Pattern 2

In loading pattern 3, an experiment was conducted by applying loading in various directions. Within experiment, 4 pressure loads were applied to the model from

opposing sides. The crown's displacement was less than the displacement created from loading pattern 2 and was equal to 1.7 mm downwards. Model deformation generated by loading is presented in Figure 4-31, and stress distribution throughout the model is illustrated in Figure 4-32. The difference in horizontal reaction forces on both sides of the model was about 780 N. The vertical reactions were proportional to the direction of load applied. Subsequently, maximum and minimum stresses' positions moved from the centre of the arc to the left side of the sample.

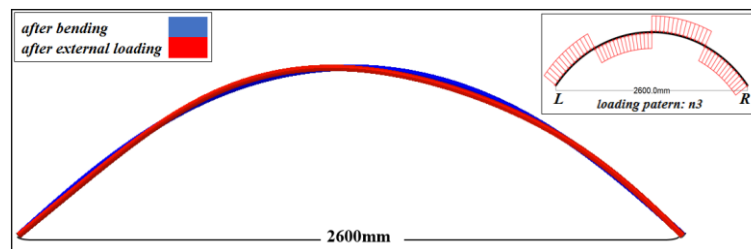


Figure 4-31: Model's Deformation under loading- Pattern 3

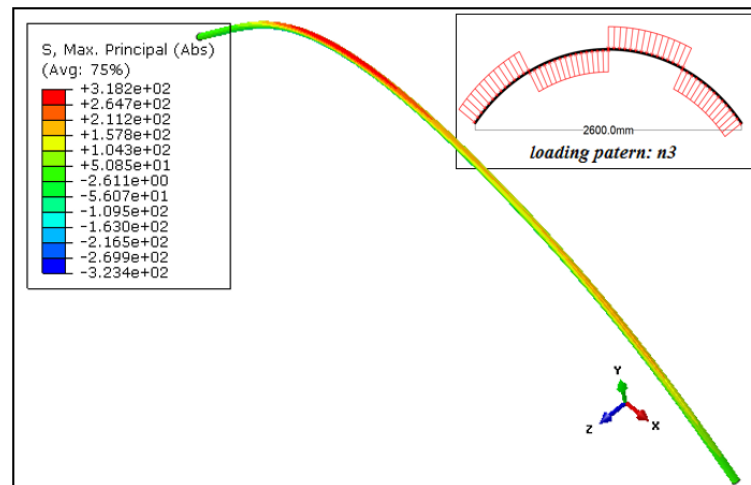


Figure 4-32: Stress distribution contour – Pattern 3

Loading patterns 4, 5 and 6 were designed that the total gravity loads applied to the models in vertical direction was equal to 2300 N, and only the distribution pattern differed between models. A gravity distributed load was applied over pattern 4' upper web. In pattern 5, the same amount of load was applied to the middle third of the model. Eventually, in pattern 6 a point load of 2300 N was applied to the centre of the model. The model's deformation under loading are presented in Figure 4-33. In loading pattern 4, after loading, the arc's crown was displaced 7mm upwards. While in loading patterns

5 and 6, after loading, the arc's crown moved downwards. According to the results obtained in pattern 5 loading, the arc displacement was equal to 21 mm, and in pattern 6 loading, 87.6 mm.

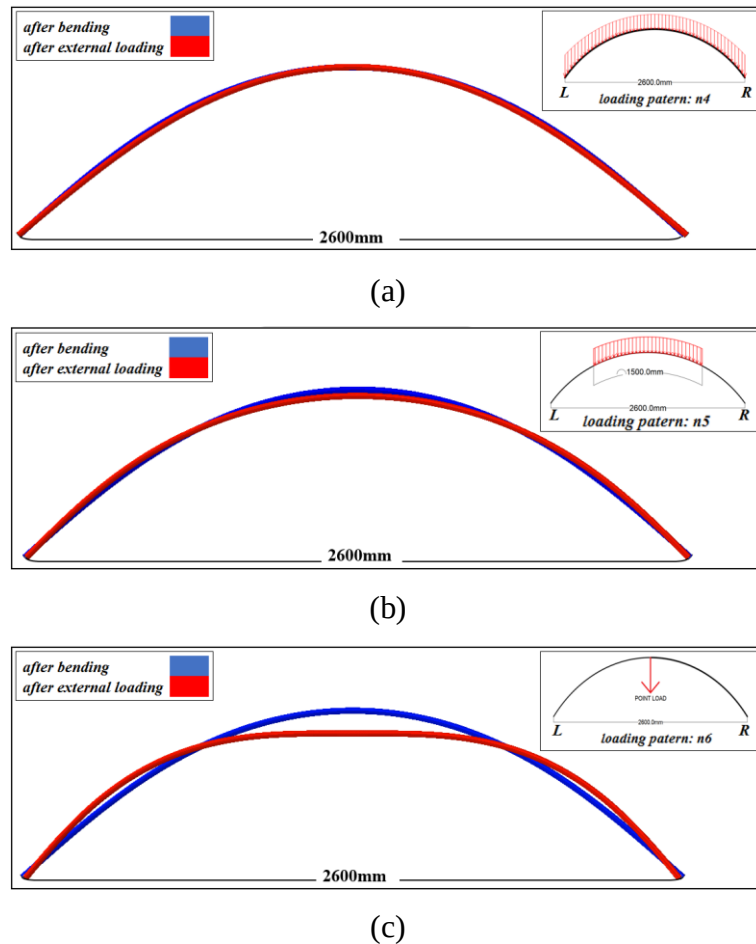
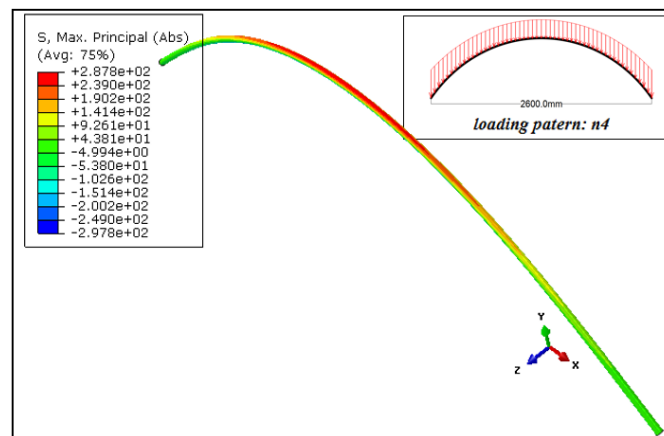


Figure 4-33: Deformations under loading: a) pattern 4, b) pattern 5, c) pattern 6.

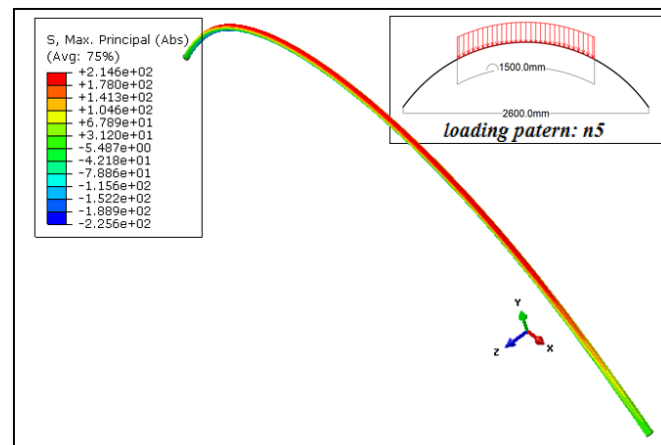
Due to the loading pattern's symmetry, the applied loads were equal in patterns 4, 5 and 6. This led both horizontal and vertical reaction forces to be equal. Horizontal reaction forces increased simultaneously with load centralization. In load pattern 4, as the load was distributed all over the sample, the horizontal reaction forces were equal to 1400 N. Whereas, in loading pattern 5, the same amount of load was distributed at the middle of the structure, creating 2100 N reaction forces at joints, and in load pattern 6 (point loading) it was equal to 2500 N. This indicated, if loading pattern changes

from centralized to distributed, there would be a significant reduction in the horizontal reaction forces.

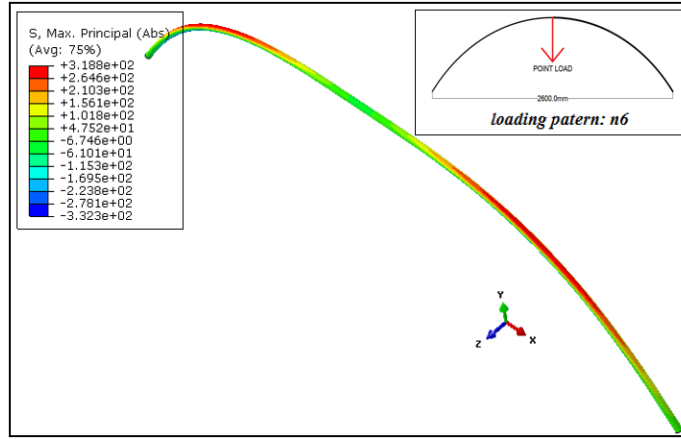
The highest stress created in these models was related to pattern 6, and the lowest stress was related to loading pattern 5. The position of the maximum stress creation varied in each loading pattern. In load pattern 4, maximum stress's position was in the middle section, whereas in loading 5, maximum stress was created at a distance of 760 mm from the centre of the model to both sides (exactly 10 mm after the load distribution area). Lastly, in loading pattern 6, this position was created at a distance of 790 mm from the centre of the model to both sides (30 mm away from the position of the formation of maximum stresses in loading pattern 5).



(a)



(b)



(c)

Figure 4-34: Stress distribution contours: a) pattern 4, b) pattern 5, c) pattern 6.

4.3.5.4. Conclusion

By considering using bending active structures in various architectural applications, models can be subjected to different loading patterns. Accordingly, the structural behaviour of such structures was investigated under various loading patterns.

From the results gathered, it was observed that structures behaved differently under various loading patterns. Although the magnitude of the loads applied in both groups (the first and second three patterns) were equal, deformations and stresses created were varied in the models. For instance, the model under load pattern 1 moved slightly upward. By comparing displacements in loading patterns 4, 5 and 6 and note that the applied load was equal in all three cases, while the displacements in all three cases differed, and a significant displacement occurred in the point loading pattern 6.

The stresses generated in the initial bending section should always be considered. If the stresses created due to external loading were aligned with the stress created in the initial bending step, the stress values could approach the material's yield stress point, and as a result, it is possible to overcome the yield stress point and led to occurrence of plastic deformations in the structure. On the other hand, when the stresses created during loading were contrary to initial stresses created, the stresses created in models reduced.

CHAPTER 5

WIND TUNNEL RESULT

In this chapter, the results of wind tunnel experiments related to wind effects on active blocking structures are investigated. Wind tunnel experiments were performed on models with different geometries in the form of the open and closed models. In addition, other cases such as the impacts of various velocities at different wind flow angles were discussed. In the final part, numerical modelling similar to laboratory models was made and results produced were compared.

5. Wind Tunnel Result

5.1. Introduction

In the present study, a design of bending active structures against wind flow were investigated. However, due to the lack of information regarding the effect of wind on bending active structures, wind tunnel testing was explored to investigate the effect of wind flow on the surface and surrounding of these structures. A GFRP form-finded model was considered for this experiment because of its elastic properties. In the following, mean pressure coefficients with respect to the various form-fined geometry in open and closed span models under different wind flow directions applied were evaluated. Numerical modelling was performed on one of the laboratory models and validated with laboratory outcomes.

5.2. Laboratory Results

In this section, results for pressure distribution in 8 active bending models against wind flow were presented. MATLAB coding software was used to process data analysis for each angle under various tested wind speed. Due to the symmetry in models' geometric shape in both parallel and perpendicular directions to the span, only results for angles of 0 to 90 degrees were presented in this work. Also, all the results are presented in Appendix D-1 separately for each experiment. In the study of the non-Gaussian distribution, only the structural model with a span of 716 mm at a speed of 10 *m/s* was evaluated.

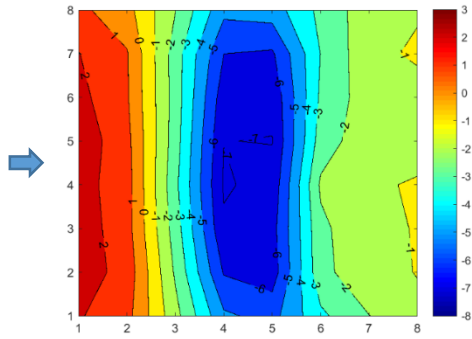
5.2.1. Mean pressure

According to the obtained results, a general trend was observed in the distribution of pressure on the active bending model's outer surface. It suggested that each part of the model facing the wind flow was under positive pressure and the other part of the structure was under negative pressure or suction.

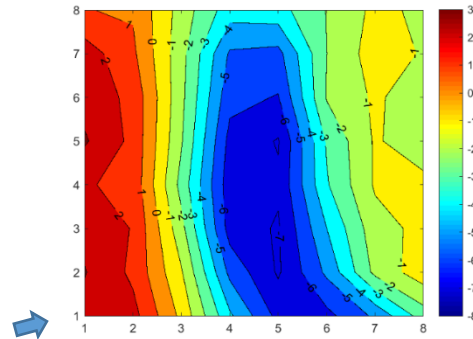
Pressure distribution on the models' surface under the wind flow parallel to the structure's span caused positive pressure on the windward side. Thus, due to the obstruction of the structure in the wind flow path, the flow re-attachment lines moved toward the roof of the structure; as a result, negative pressure or, in other words, suction was obtained. Due to the phenomenon of separation flow, the maximum mean negative pressure occurred at the top of the structure (crown's peak). Following the movement of the re-attachment lines over the top of the structure and reaching to the back of the structure, the recirculation region and the vortices were created. Vortices formed at leeward caused negative pressure, given that it was much lower than the negative pressure created at the top of the structure. With changing wind flow direction applied to the structure, the maximum suction's position changed from the top of the structure towards the edge (these changes were more obvious in low-rise models). Eventually, under the wind flow perpendicular to the span, maximum suction arose on the structure's edge. The colour contour of the mean pressure distribution under wind flow for 816 mm model, in both open and closed models, at a speed of 4 *m/s* are presented in Figure 5-1 and Figure 5-2. Similarly, the same contours and data are provided for all models in Appendix D-2.

In low-rise models (916 mm model) an exception was observed at the structure's leeward area. Due to the weaker vortex and the reconstruction of pressure at the back of the structure, a positive pressure observed near the ground. Positive pressure observed between the angles of 15, 30, 45 and 60 degrees. It should be noted that the pressure created was very small. The positive pressure range created at the back of the closed models were more significant than open models.

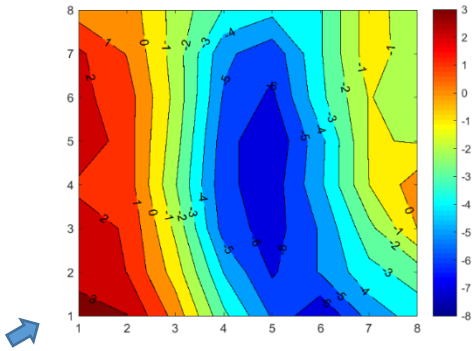
Chapter 5: Wind Tunnel Results



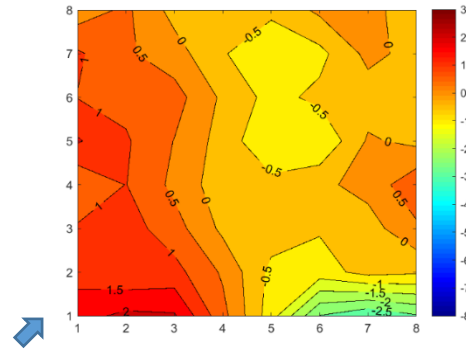
0 degrees



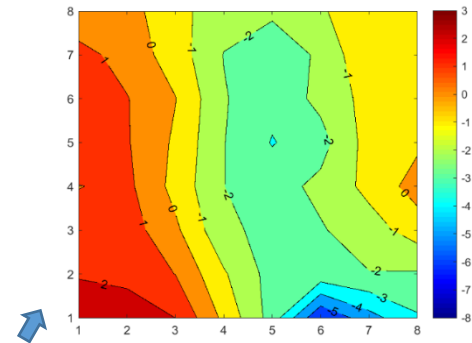
15 degrees



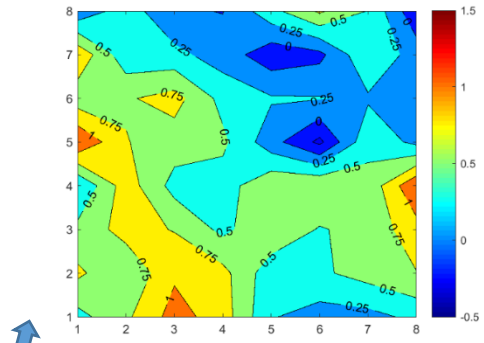
30 degrees



45 degrees

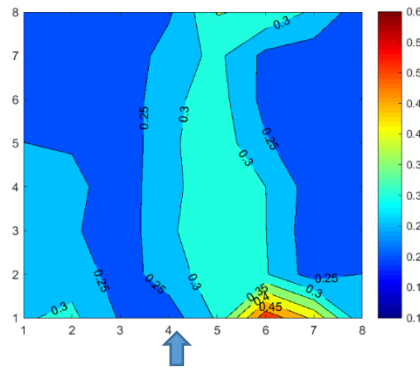


60 degrees



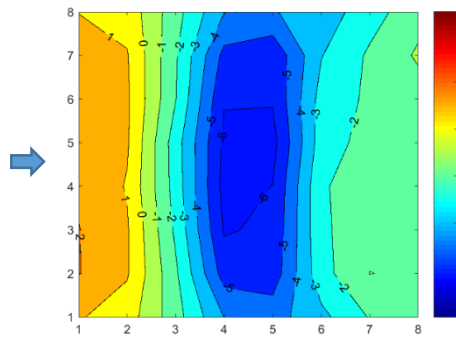
75 degrees

Chapter 5: Wind Tunnel Results

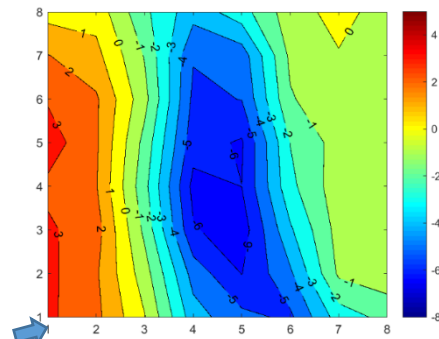


90 degrees

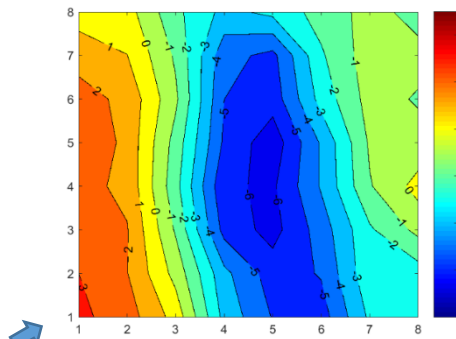
Figure 5-1: MO816's mean pressure coefficient colour contour at the velocity of 4 m/s



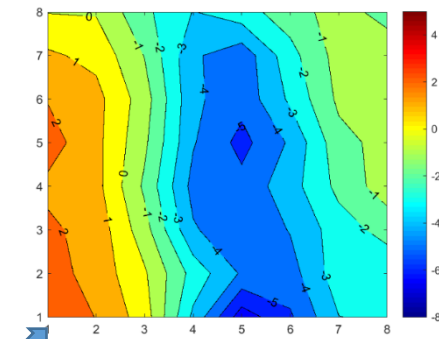
0 degrees



15 degrees



30 degrees



45 degrees

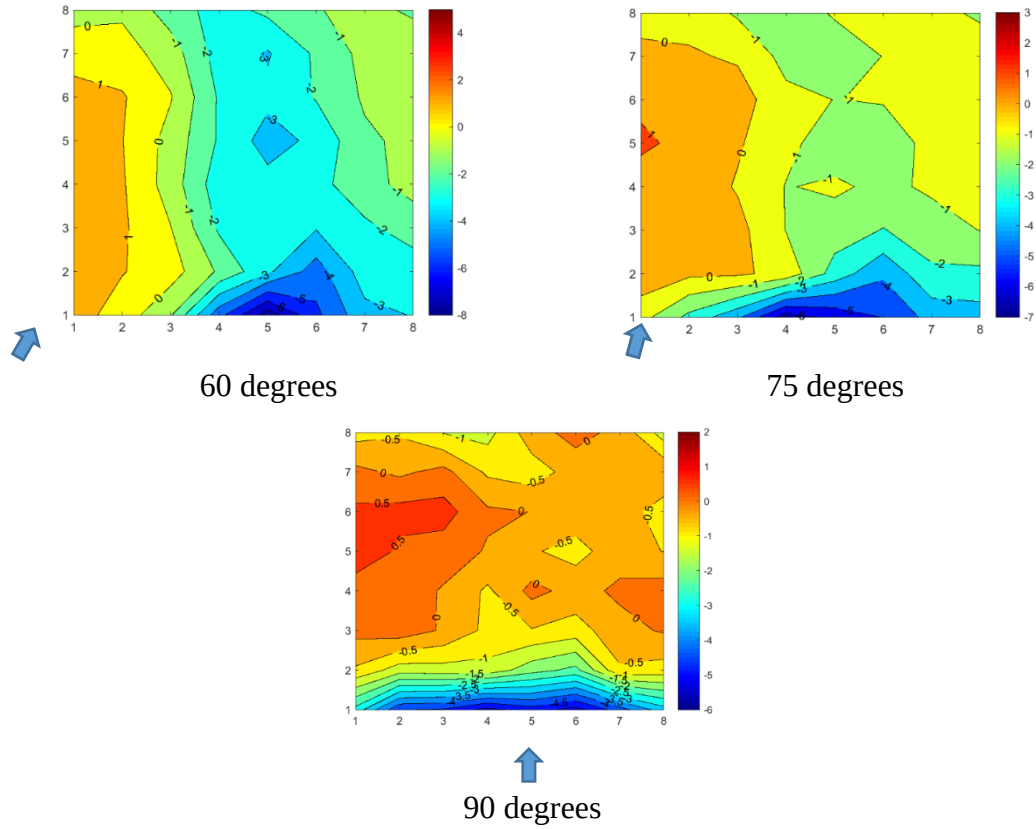


Figure 5-2: MC816's mean pressure coefficient colour contour at the velocity of 4 m/s

The pressure changes for each model proportional to the velocity changes are presented in Figure 5-3. According to the general principles, increasing the speed raises pressure on the surfaces. Generally, by increasing velocity from 4 m/s to 6 m/s, the range of positive and negative pressure changes were almost doubled. In this regard, doubling the velocity (from 4 m/s to 8m/s), the changes in positive and negative pressure range rose by three to four times, respectively. Finally, with increasing velocity from 4 m/s to 10m/s, the increased value in positive and negative pressure ranges were approximately four to five times. From the results obtained, the changes in pressure ranges in the negative pressure (suction) were greater than the positive pressures. With the increase in the velocity from 4 m/s to 6 m/s in closed models, the increase in positive pressure was about one and a half times, which was lower than the increase in positive pressure in open models.

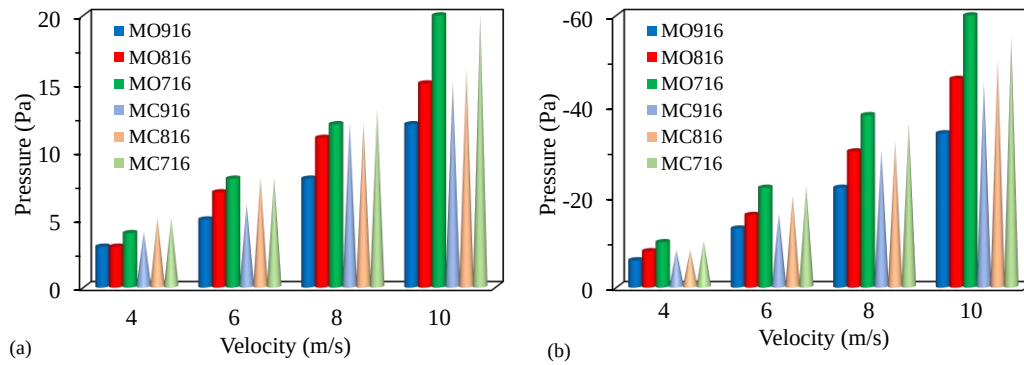


**Figure 5-3: The range of pressure changes on the surfaces for each model a) Maximum pressure
b) Minimum pressure**

5.2.2. Mean pressure coefficient and r.m.s pressure coefficient

To better evaluate the pressure distribution on the surface of the models, mean pressure values and root mean square (r.m.s) were assessed. To investigate the wind effect on the models, testing at various angles was considered as an important principle. In Figure 5-4 and Figure 5-5 Mean pressure coefficients and r.m.s pressure coefficients are presented at velocities of 4 m/s and 10m/s. As the velocity increased from 4 m/s to 10m/s, no significant changes were observed in the mean pressure and average squares of pressure coefficients on the outer surface of the active bending models. This showed Reynolds number did not have a significant effect on the results. However, as the velocity increased, the structure's performance changed, and the mean pressure coefficients became more regular. Significant changes in r.m.s pressure coefficients were observed in the areas, which was under high suction. At a perpendicular wind flow angle to the span, these changes were observed at the edge of the models. Mean pressure distribution contours for symmetrical angles are given in detail in Appendix D-3. As the velocity increased, the angles which were in the diagonal direction relative to each other had a better match.

Chapter 5: Wind Tunnel Results

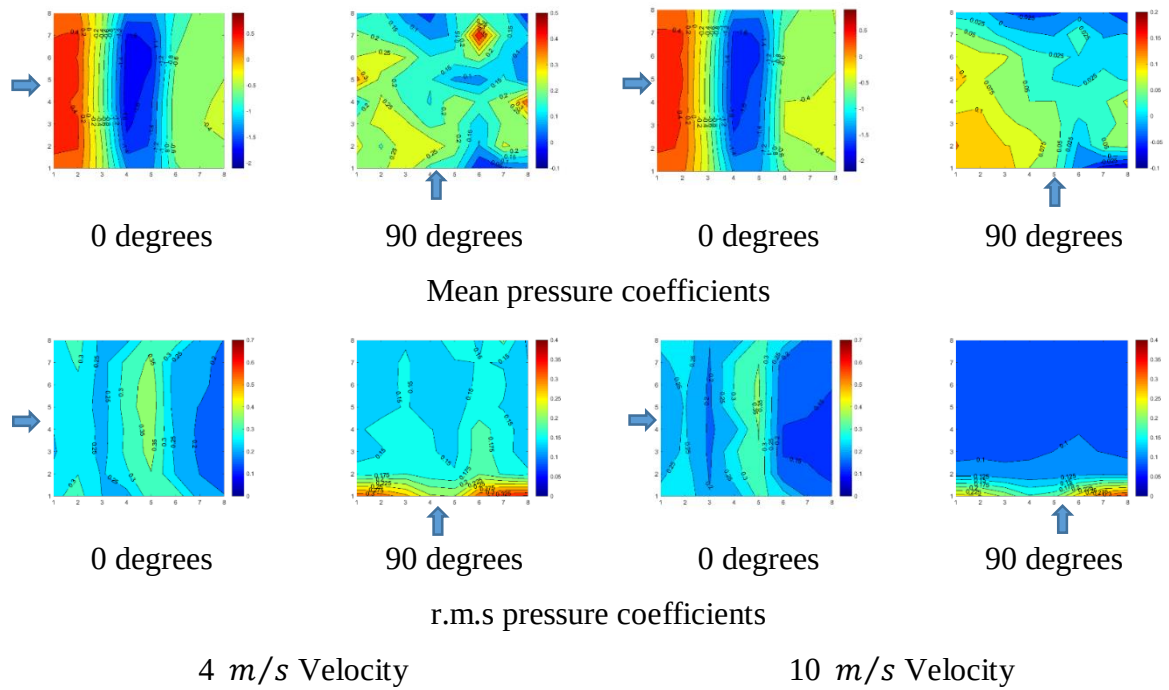


Figure 5-4: Mean and r.m.s pressure coefficient in MO716 at two angles of 0 and 90 degrees

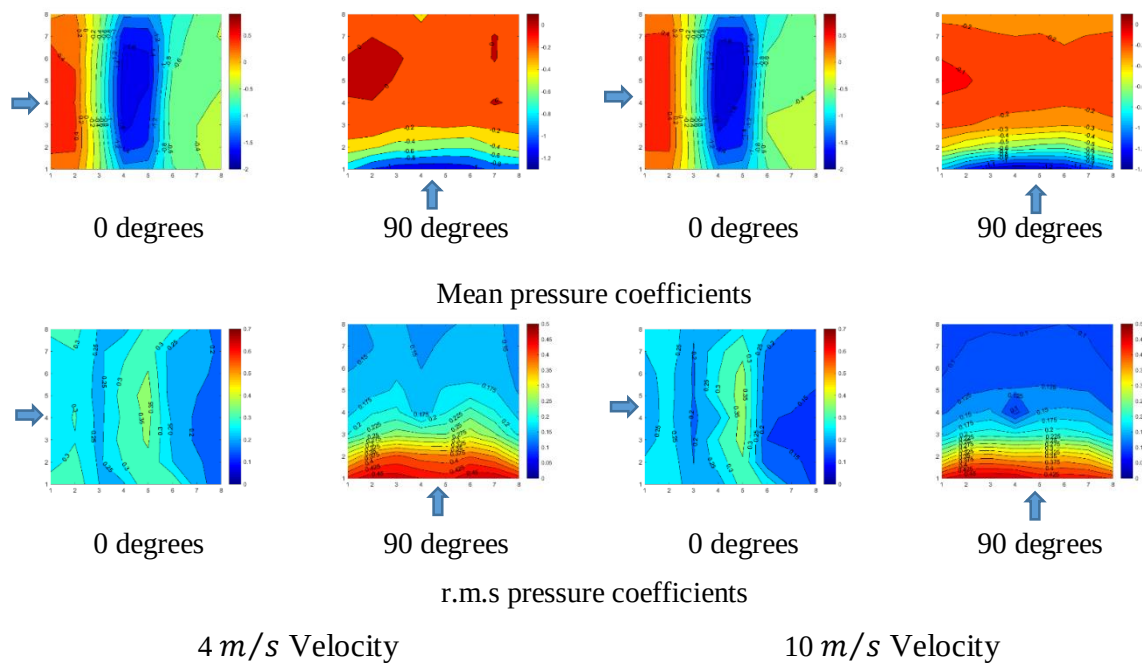


Figure 5-5: Mean and r.m.s pressure coefficient in MC716 at two angles of 0 and 90 degrees

Due to the structure's low height, it was expected that the models would function similarly to low-rise buildings. The flow direction perpendicular to the models' span (90 degrees angle), streamlines collided with the roof's edge and caused the phenomenon of flow separation, and as a result, maximum suction occurred. Then, due to the structure's length, these lines reattached, and variation in pressure coefficients became limited and gentle. Also, at the back of the structure, because of separation flow, limited suction occurred.

In addition, when dome shape structures face wind flow, an area of horseshoe vortices is created in front of the structure near the ground. A very limited increase in pressure coefficient was observed in the middle line from the lowest position of the windward near the ground. Subsequently, the windward side's pressure coefficient reached its maximum value, and the downward trend was perceived. In this study, according to the changes in pressure coefficients in the middle line, the occurrence of horseshoe vortices in the model with a 716 mm span was observed.

5.2.3. Open and closed models' comparison

Laboratory modelling was studied in both open and closed span models. Using the results obtained, the following outcomes were conducted from the differences between these two modelling modes.

Two parts were created by dividing the span in relation to the axis symmetry perpendicular to the length of the structure. The section facing wind flow was called b_w and the section on the opposite side called b_L as shown in Figure 5-6.

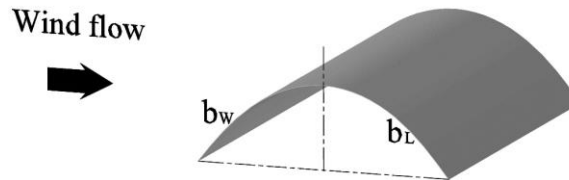


Figure 5-6: Divided input spans of model into two parts b_w and b_L

By altering the wind flow direction, each time one of the span's sections was exposed to wind flow (b_W), the other part (b_L) experienced suction in the structure. In open models, as wind flow angle became closer to perpendicular to span, suction reduced on the structure's roof and moved closer to b_L area. In open models, with approaching wind flow direction perpendicular to span (angle of 90 degrees), the pressure distribution was very limited, and slight compression and suction were applied to the structure. Furthermore, due to the thin thickness of the active bending model against wind current, a sharp decrease in pressure was observed under wind flow, perpendicular to the structure's opening. In closed models, by changing wind flow direction, suction occurred in b_L area and as wind flow direction approached perpendicular to the span, suction was obtained at the edge of the model (similar to low-rise buildings) due to separation flow.

As previously discussed, suction was created when the currents hit the edge of short models. Whereas in the open models, no suction was observed at the edge. This can be attributed to the very thin thickness of the model against wind currents. This difference expressed in the model's edge pressure coefficient can be seen in Figure 5-7. According to the pressure gauge valves position on the sample's surface, the transverse lines of the pressure gauge valves were numbered 1 to 8 (Figure 3-37(a)). The mean pressure coefficients values on these lines were plotted relative to the distance X/B . B represented the length of the model equal to 1020 mm and X indicated the longitudinal coordinates of each pressure gauge valve on the model. Likewise, Figure 5-8 presents a comparison of mean pressure coefficients at 90 degrees and the stated difference can be clearly observed on the edge of the model (line No. 1). In closed models the average mean pressure coefficient values at the wind flow perpendicular to span in line No. 1, were observed to be 92% higher than the open models. In other words, higher suction was observed on the edge of closed models. The presence of panels at the both sides of the model and no current flowing under the model created this significant change.

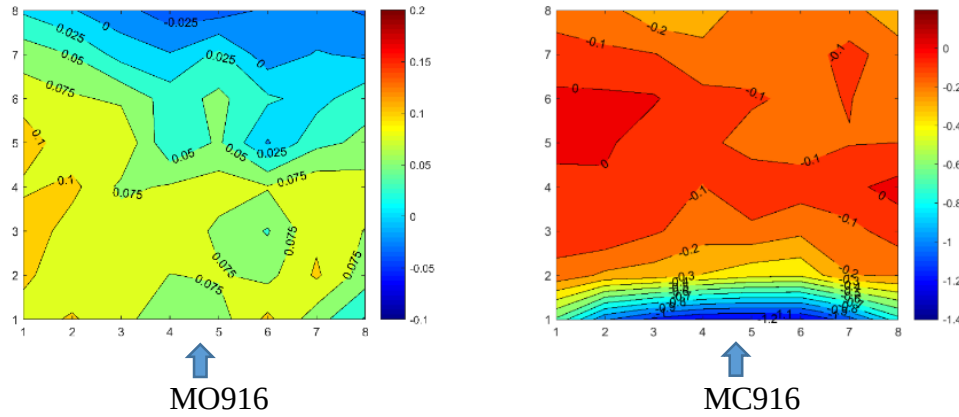


Figure 5-7: Mean pressure coefficient under 90 degrees angle with the velocity of 6 m/s

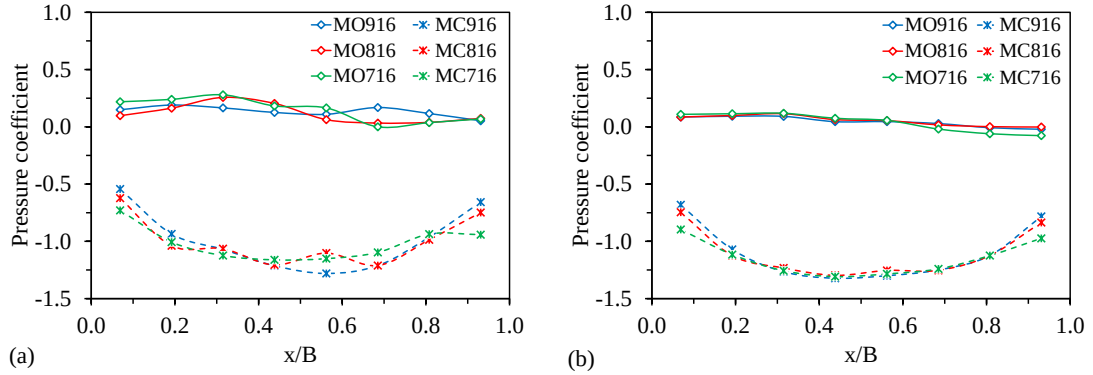


**Figure 5-8: Mean pressure coefficient on the edge of structure (line No. 1) under 90 degrees angle
a) velocity of 4 m/s b) velocity of 10 m/s**

In order to study the pressure coefficients trend more analytically, pressure coefficients on line No. 4 at two different velocities are plotted in Figure 5-9. Pressure coefficient in models had no significant difference between open and closed models in both velocities. However, differences were observed in the 816 mm model at 4 m/s velocity on the windward side. This pattern was only observed in this case, which could be due to laboratory errors.

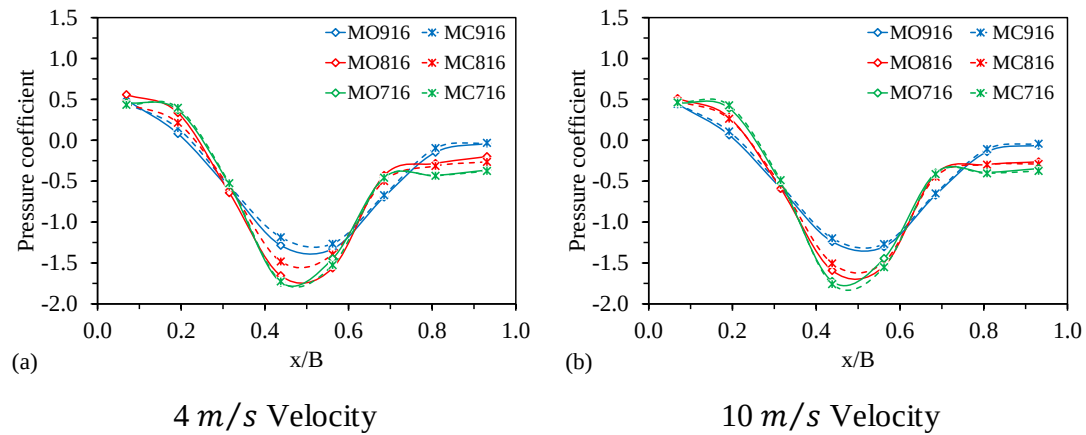


Figure 5-9: Pressure coefficients for the mid line (No. 4) in both open and closed spans models at 0 degrees a) 4 m/s velocity b) 10 m/s velocity

Pressure coefficients in lines No. 1 and 8 (nearest lines to opening spans) are presented at two angles of 30 and 60 degrees for the 716 mm model in Figure 5-10 and Figure 5-11. Pressure coefficients in open models at the angle of 30 degrees in line 1 and at the leeward area indicated more suction compared to closed models. However, at the 60 degrees angle, wind flow behaved differently. This differences between the two open and closed models in line No. 1 occurred at not only the leeward side but also the windward side. Thus, in closed models, mean negative pressure coefficients (suction) at the top of the structure were more than in the open models, while suction in the leeward area in open models was greater than suction created in the closed model. Furthermore, in line No. 1, the mean positive pressure coefficient applied in the open models was higher than the closed model. It can be observed in line No. 1 at the angle of 60 degrees with closing the structures' sides, positive pressure coefficient diminished and negative pressure coefficients at the top of the model increased. The difference was also observable in lines No. 4 and 8; however, compared to line No. 1, this difference was not significant. The reason for the difference in the suction of line No. 1 in both open and closed span models can be attributed to the presence of flow under the open model. Due to the presence of current the negative pressure created on the surface reduced.

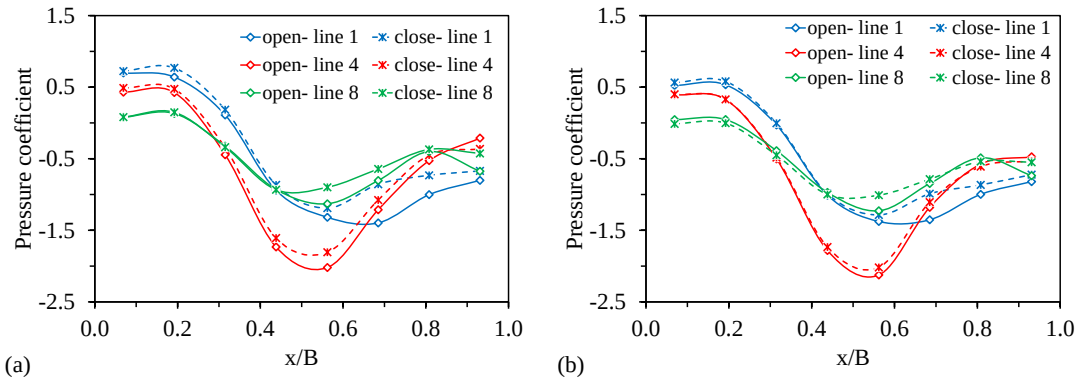


Figure 5-10: 716 mm model's pressure coefficients at both closed and open models at 30 degrees angle wind flow under a) 4 m/s velocity b) 10 m/s velocity

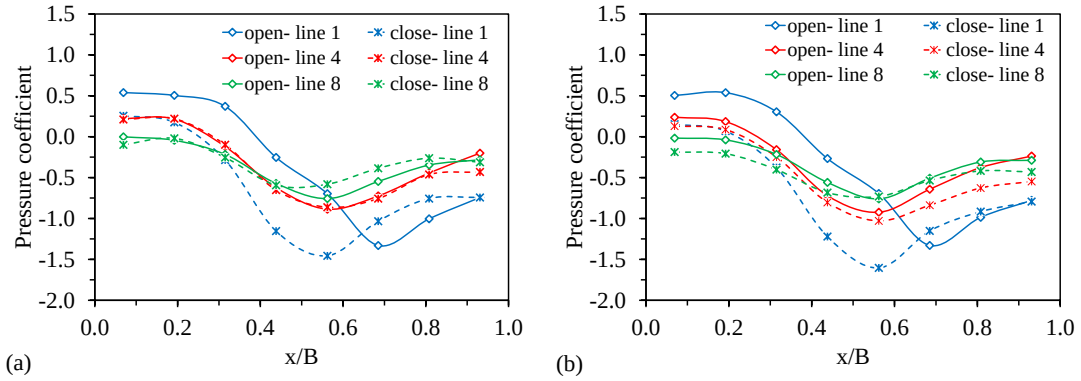


Figure 5-11: 716 mm model pressure coefficients at both closed and open models at 60 degrees angle wind flow with a) 4 m/s velocity b) 10 m/s velocity

Studies on these two angles for the 916 mm model at a wind flow angle of 30 degrees in line No. 1 and the leeward area showed that the suction created in the closed model was greater than the suction in the open model (Figure 5-12). This was opposite to the result obtained from the 716 mm model. Also, some differences were obtained between open and closed models at line No. 8. For example, in the closed models, the positive pressure coefficient at the windward side and suction created at the leeward area was less than the pressure created in open models. However, at an angle of 60 degrees in two lines of No. 4 and 8, the range of pressure coefficient along the structure decreased and therefore, the difference between the open and closed models declined as presented in Figure 5-13. Nevertheless, in line No. 1, the positive pressure on the windward side

decreased in the closed models, and the suction created near the top of the models increased. The results for the 816 mm model are presented in Appendix D-4.

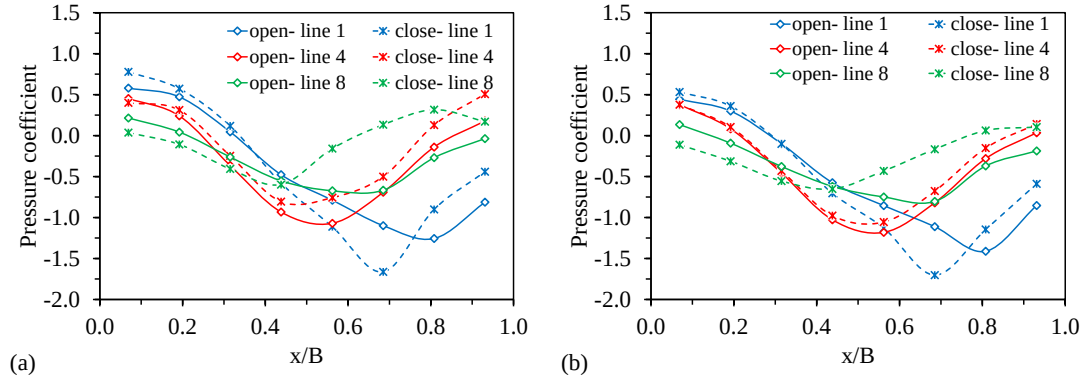


Figure 5-12: 916 mm model pressure coefficients in both closed and open models at 30 degrees angle wind flow a) 4 m/s velocity b) 10 m/s velocity

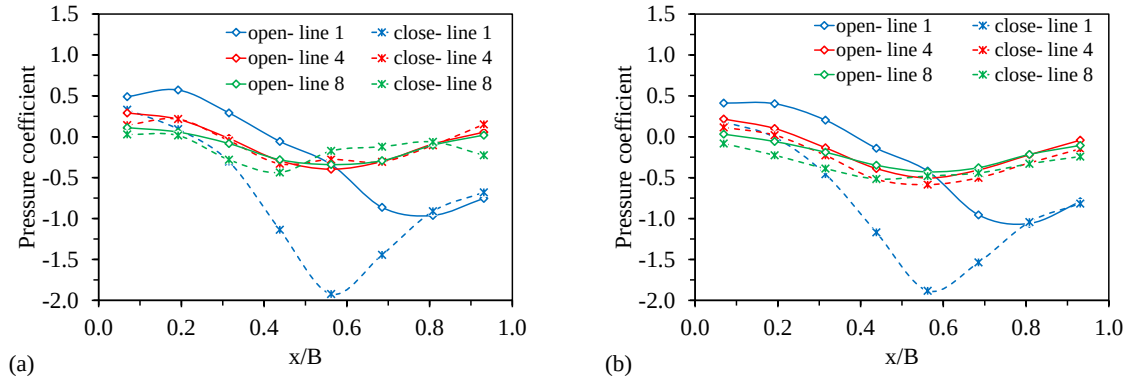


Figure 5-13: 916 mm model's pressure coefficients in both closed and open models at 60 degrees angle wind flow a) 4 m/s velocity b) 10 m/s velocity

Pressure coefficient changes along the latitudinal dimension of the models under wind flow perpendicular to the span (90 degrees) are presented in Figure 5-14. The ratio $y/D = 0.04$ represented the edge close to the wind flow (line No. 1) and the ratio $y/D = 0.95$ represented the edge farther from the wind flow (Figure 3-31). Lines D and E represented the top part of the models (Figure 3-37). In general, changes in both open and closed models at 10 m/s velocity were more stable and regular compared to 4 m/s velocity. In closed models, maximum suction was created at the top of the models, and then suction was reduced along with the structure until finally, it reached a balance. In the open models, the positive pressure was first observed, and then the suction was observed along with the models. It must be noted that these changes in the

pressure coefficients in the open models were minor. Lines D and E were symmetrical with respect to the axis perpendicular to the structure's span. However, the asymmetry was observed in the results. This asymmetry was more expressed in open models, especially at 4 m/s velocity. Seemingly, at low velocities, the performance of the structure with respect to wind flow showed resistance which was expected on account of energy stored in the models from the initial form-finding step.

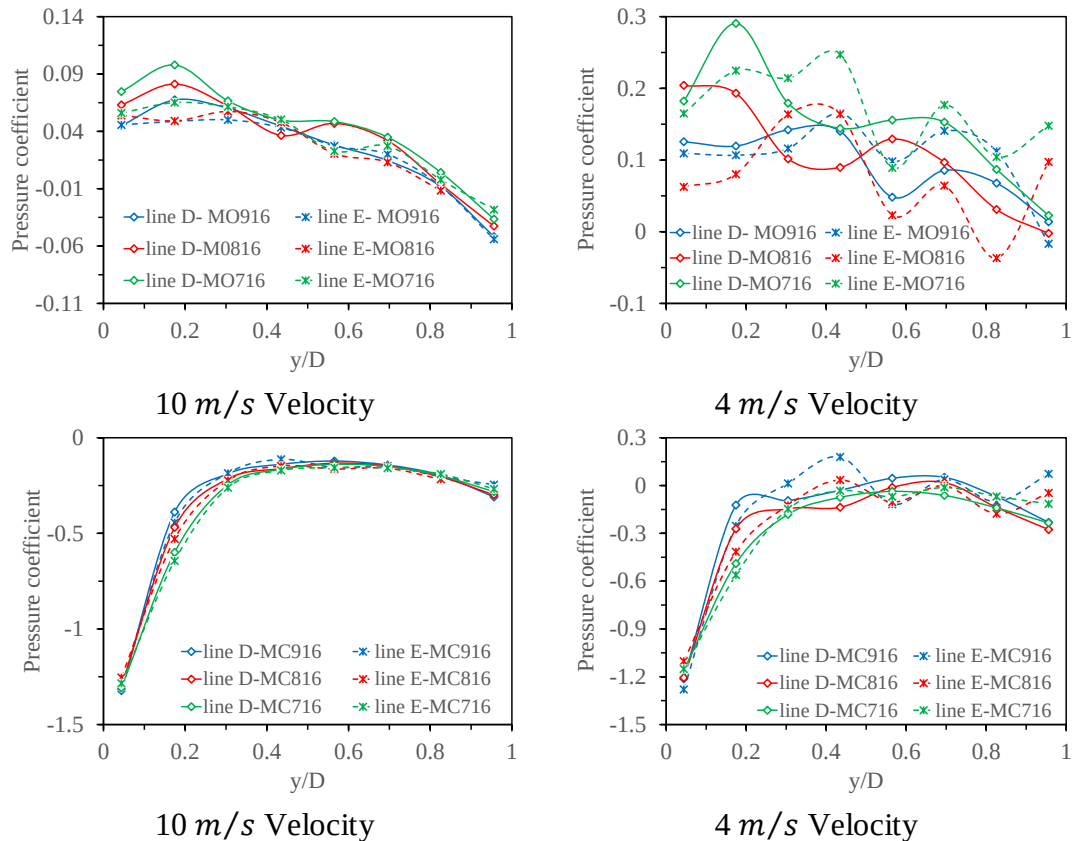


Figure 5-14: Pressure coefficient at 90 degrees wind flow in both closed and open models

5.2.4. Effect of wind flow directions on pressure coefficient

In this clause, the effect of wind flow directions on the pressure coefficient was investigated. The mean pressure coefficient regarding four pressure gauge valves (No. 1, 4, 33 and 36) in both open and closed models at velocities of 4 m/s and 10 m/s under various wind flow directions are presented in Figure 5-15 and Figure 5-16. Pressure gauge No. 1 in the open models at both speeds from zero to 90 degrees with a 15 degrees step was fully expressed positive pressure coefficient while in the closed

models, after the angle of 75 degrees expressed negative pressure coefficient. In pressure gauge No. 4 at the velocity of 4 m/s no suction was recorded in both open and closed models. But with increasing velocity, closed models showed a negative pressure from the angle of 75 degrees. Pressure gauge No. 33 in open models illustrated the highest suction at the angle of 15 degrees, and by passing a 15 degrees angle, negative pressure coefficient decreased until it approached zero at 90 degrees. Further, in closed models, the highest negative pressure was observed at 60 degrees. In pressure gauge No. 36, maximum suction occurred at a 30 degrees in both open and closed models. It should be pointed out that, at the model 916 mm, maximum negative pressure coefficient occurred at the 0 degrees. After passing 30 degrees suction created on the model decreased as it approached zero at the 90 degrees. High suction at some angles was resulted from separation flow near the corresponding pressure gauge valves. A general trend was observed for all models and the highest values of the mean pressure coefficient were observed at the crown.

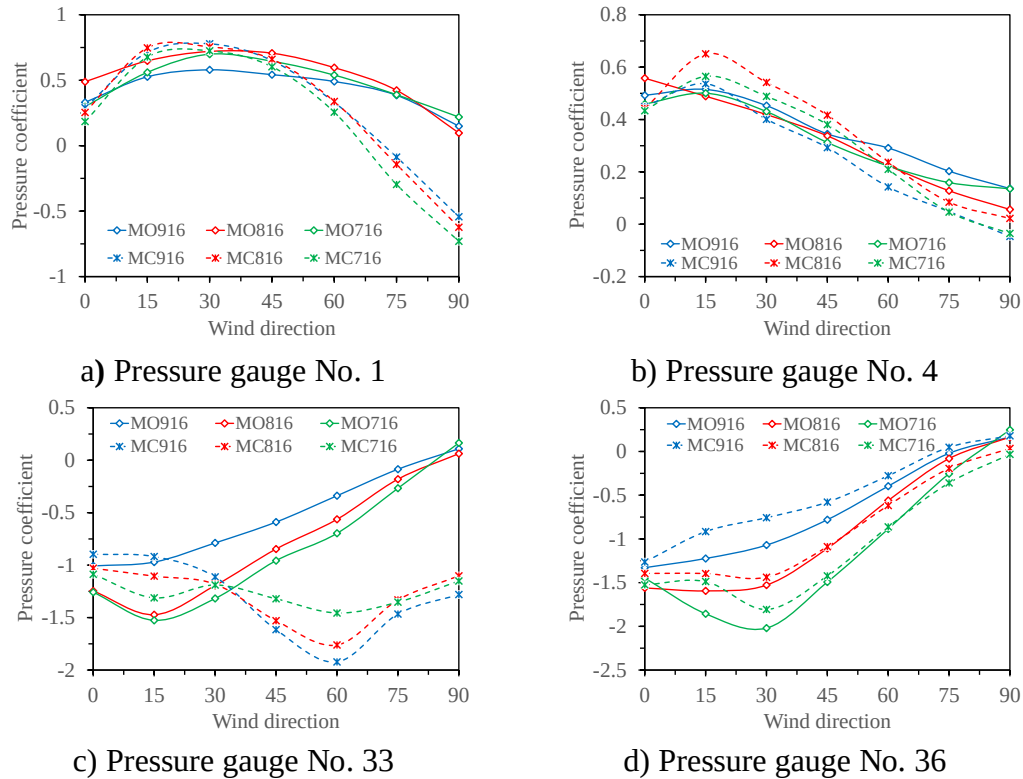


Figure 5-15: Mean pressure coefficient at the specified location under 4 m/s velocity

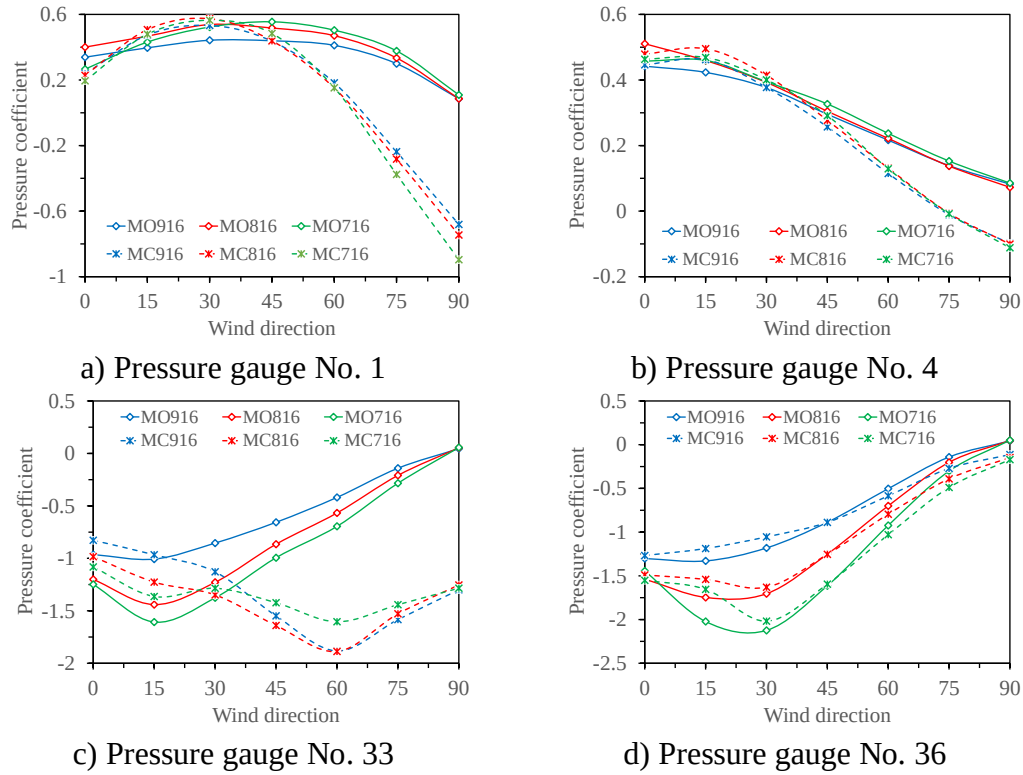


Figure 5-16: Mean pressure coefficient at the specified location under 10 m/s velocity

5.2.5. Maximum and minimum mean pressure coefficient

This section presented the maximum and minimum mean pressure coefficients at each velocity applied at different angles. As illustrated in Figure 5-17(a) and Figure 5-17(c), maximum mean pressure coefficient in model 716 mm was observed at 4 m/s velocity, and as velocity increased, mean pressure coefficient decreased. In fact, the structure's response to the wind flow velocity of 4 m/s was different from other wind flow velocities applied. However, wind speeds of 6, 8 and 10 m/s had almost the same behaviour. It could be inferred that with increasing velocity, the behaviour of the structure became monotone. In open models, the lowest values were obtained at perpendicular angle to the structure's span (90 degrees). This was as the result of the thin thickness of the model exposed to wind flow. According to the data obtained from Figure 5-17(b) and Figure 5-17(d), the minimum mean pressure coefficient was obtained at 30 degrees angle. Appendix D-5 represents the minimum and maximum mean pressure coefficients for the other models.

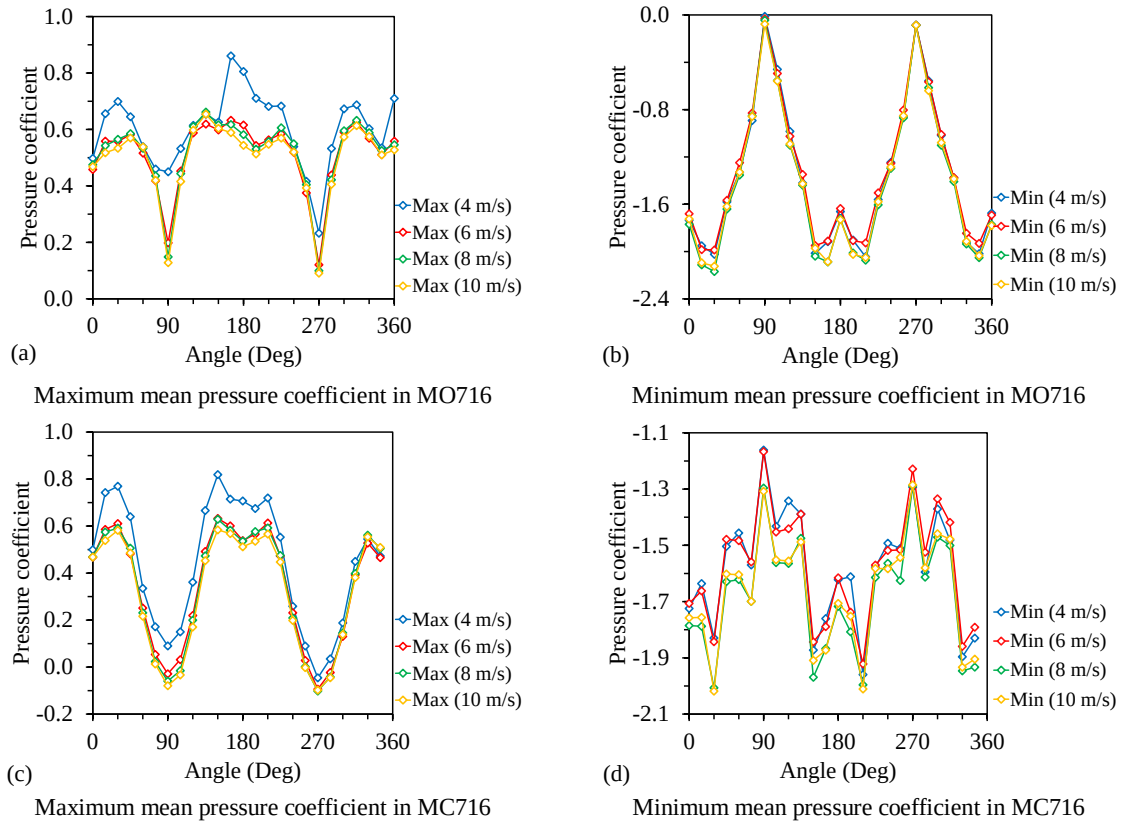


Figure 5-17: Maximum and minimum mean pressure coefficient at different wind directions

The minimum mean pressure coefficient (maximum suction) for each model is presented in Table 5-1. According to the results obtained, in the MO916 model, an angle could not be stated for the maximum negative pressure coefficient. However, over 360 degrees wind flow, under two angles of 30 and 210 degrees, maximum suctions were identified. By miniaturizing the secondary span's length, maximum suction occurred at the angles of 15 and 30 degrees in both MO816 and MO716 models. Results were obtained differently in the closed models that the maximum negative pressure coefficient in both MC916 and MC816 models was obtained at the same angle of 60 degrees. While in the MC716 model, similar to the open models, it occurred at the angle of 30 degrees. Simply put, in closed models, maximum suction occurred at a greater wind angle compared to open models. Only in model 716mm both the maximum suction created and the wind flow angle which maximum suction occurred

under that angle were same in both open and closed models. It could be concluded that two factors of the panelling at the model's side and the height (f) of models played an effective role in expressing the critical angle and pressure coefficient values.

Table 5-1: The wind direction angle causing maximum suction on structure

Model	MO916	MO816	MO716	MC916	MC816	MC716
Angle (deg)	*_	15	30	60	60	30
Pressure coefficient	-1.4	-1.7	-2	-1.8	-1.9	-2
*The expression of a specific angle was not possible.						

5.2.6. Variation of pressure coefficient due to various f/L ratio

In this section, an inquiry into the effect of the various height to span ratio on pressure distribution was raised. As illustrated in Figure 5-18, in open models with increase in the f/L ratio, maximum suction occurred in the 816 mm model at the angle of 15 degrees and in the 716 mm model at the angle of 30 degrees. While in closed models, with the increase in the ratio, maximum suction occurred at a smaller angle perpendicular to the structure's span. In 916 mm and 816 mm models, maximum suction was created at an angle of 60 degrees and in the 716 mm model at 30 degrees. At the top of that, maximum suction's location varied depending on the height of the models. Thus, in 916 mm and 816 mm models, maximum suction happened in the b_L area. Yet, in the 716 mm model, this maximum value occurred at the top of the models. It should be taken into consideration that in 916 mm and 816 mm closed models, the maximum suction was obtained only in a local area and one pressure gauge valve. Figure 5-18 illustrates the pressure coefficient contours at the critical angles at $10m/s$ wind velocity.

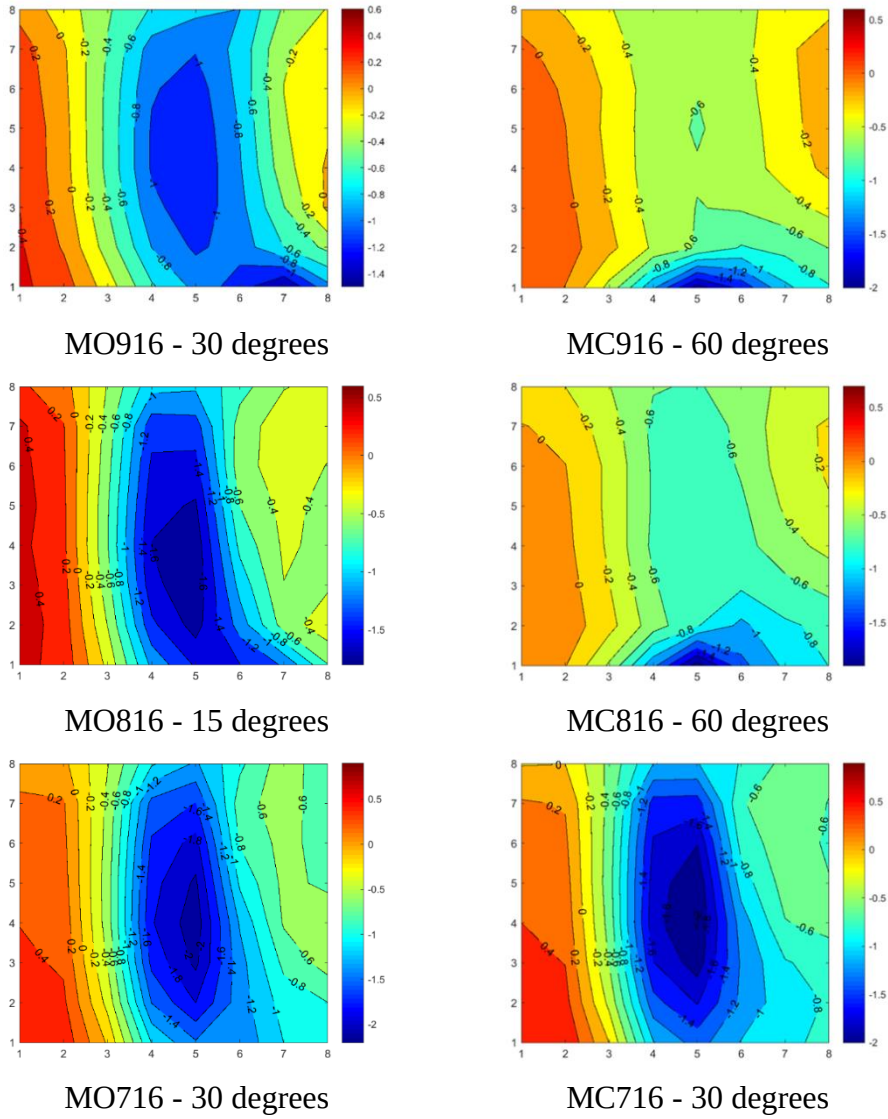


Figure 5-18: Mean pressure coefficient at the critical angle at 10 m/s velocity

As indicated, by changing the wind flow angles from parallel to the model's span, suction was created in the b_L area (line No. 1). Also, with increasing the flow angle, the suction created in the b_L area (line No. 1) was more significant than suction generated at the top of the models. The results demonstrated that, the maximum suction in 916 mm model occurred at the angle of 15 degrees. Whereas in the 716 mm model, this relocation occurred at 60 degrees. Therefore, with increasing the f/L ratio, suction in the b_L area (line No. 1) increased, arguably due to the transition of wind flow angle

from 15 degrees to 60 degrees. Figure 5-19 presents pressure coefficients on the pressure valves lines in proportion to f/L ratios. Results for the rest of the models are presented in Appendix D-6.

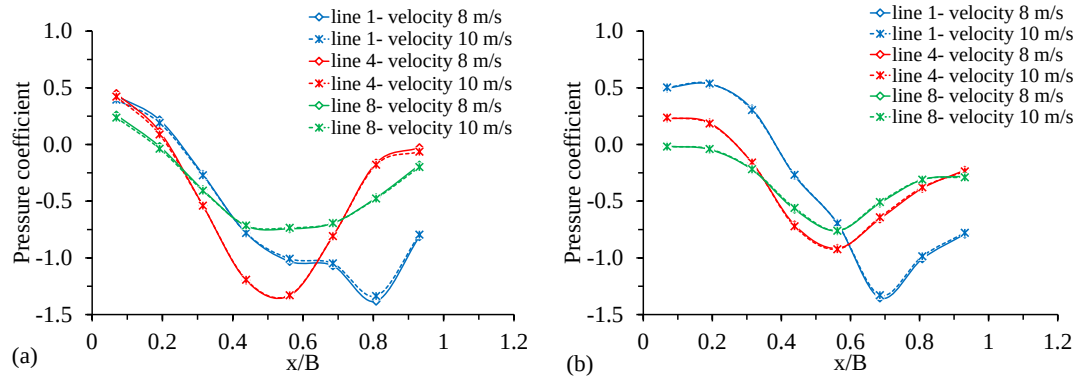


Figure 5-19: Pressure coefficients on the pressure taps lines in open models at the velocities of 8 m/s and 10 m/s a) MO916 in the angle of 15 degrees b) MO716 in the angle of 60 degrees

In 716 mm model, the decreasing trend of pressure coefficient was not observed on the windward side. Instead, first the trend was upward and then a decrease in pressure coefficient was illustrated. Also, as the f/L ratios increased, maximum suction occurred at the top section before reaching the middle of the structure. As comprehend from Figure 5-20, maximum suction at the ratio of $f/L = 0.44$ and $f/L = 0.22$ occurred in the range distance of $x/B < 0.5$ and $x/B \geq 0.5$, respectively. In other words, at 916 mm, 816 mm and 716 mm models the maximum suction at x/B were equal to 0.52, 0.5 and 0.47, due to flow separation. If the starting point of equalization of the pressure coefficients at leeward can be expressed as the point of separation flow occurrence; thus, it can be illustrated that the two 716 mm and 816 mm models had the same separation flow position. While in 916 mm model, the separation flow was observed at $x/B = 0.8$. It is worth noting that the rise in f/L ratios increased the mean pressure coefficients in the models.

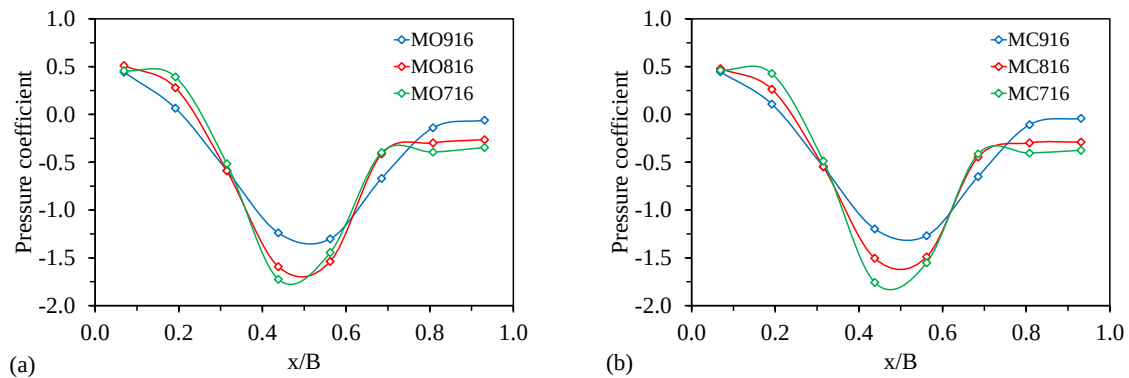


Figure 5-20: Pressure coefficients in line No. 4 at 0 degrees at 10 m/s velocities a) open models b) closed models

At zero degrees wind flow in the leeward area, a pressure coefficient area with the same value in both open and closed models was observed and presented in Table 5-2. As pressure coefficient was equal in both closed and open models, only the height of the models could affect the negative pressure values at the leeward section. It could be suggested that increasing the f/L ratio led to an increase in suction. In accordance with the obtained outputs, the lower the structure's height was, the less resistance to wind flow was and the smaller pressure coefficients was applied to the models. Moreover, from Figure 5-21, it was apprehended that pressure coefficient area covered a larger areas with increasing the structure's height. In other words, In low-rise models the pressure coefficient area was constant between line G and line H. However, with increasing height, this area also shifted to line F. Contours for all models at maximum and minimum velocity, presents in Appendix D-7.

Table 5-2: Pressure coefficients at the back of the structure with the flows parallel to the span

Model	MO916	MO816	MO716	MC916	MC816	MC716
Pressure coefficient	-0.2	-0.4	-0.6	-0.2	-0.4	-0.6

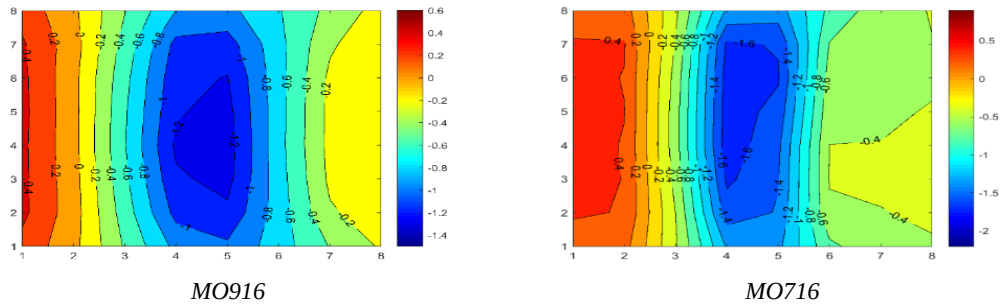


Figure 5-21: Pressure coefficients at 0 degrees under 10 m/s velocity

5.2.7. Probability Density Functions (PDF)

The probability density function is a statistical parameter that describes the probabilistic distribution of random variables. This function is an important component in studying the non-Gaussian properties of wind pressure on structures. Thus, the probability density function for pressure coefficients was calculated and compared using Gaussian distribution. These steps were implemented in MATLAB coding software, using the following code for each corresponding pressure gauge valve for a period of 200 seconds.

```
[mu, sigma] =normfit (tap pressure)
[f, xi] =ksdensity (tap pressure);
Plot (xi, f, '.');
Hold on;
y=-3:0.1:3; dd= normpdf (y, mu, sigma);
Plot (y,dd,'r-')
```

To investigate the probabilistic distribution of random variables, model 716 mm under 10 m/s wind velocity was chosen. For this purpose, pressure coefficients' time history is illustrated in Figure 5-23 and Figure 5-24. In addition, the probability density function curve for a specified pressure gauge valve at zero degrees wind flow in both open and closed models was presented. The selected pressure valves were No. 12 on the windward side, No. 17 on the windward side (locating on line No. 1), No. 36 at the top of the model, No. 41 and 48 on the leeward side locating on lines No. 1 and 8, and finally pressure gauge No. 60 in leeward side and close to the ground as presented in

Figure 5-22. In terms of wind flow perpendicular to span for both open and closed models, results are provided in Appendix D-8. Also, the probability density function curve for all pressure gauges at two angles of zero and 90 degrees attached in the general Appendix D-1.

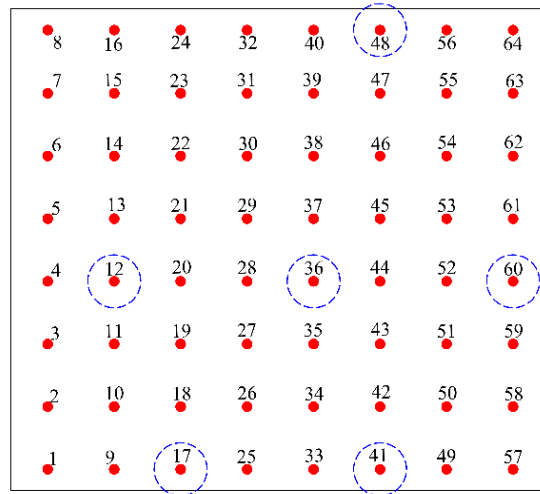


Figure 5-22: Selected pressure gauges

According to Figure 5-25, most asymmetry distribution was observed in pressure gauges No. 41 and 48 located on the leeward side in the open model. Some asymmetry distribution was noted in pressure gauge No. 12, and the same trend was observed in closed model (Figure 5-26). At 90 degrees angle, in both open and closed models, only the pressure gauges located on line No. 1 (pressure gauges No. 17 and 41) were more asymmetrical. Furthermore, by reaching to the middle part of the model, symmetry distribution was observed, and then at the end of the model (line No. 8), asymmetry was observed again with less difference compared to line No. 1. At zero degrees angle in both closed and open models, the pressure valves No. 17 and 36 presented the Gaussian distribution. Moreover, in pressure gauge valve No. 60 located at the back of the structure, symmetry with kurtosis greater than 4 was observed. At 90 degrees angle, the pressure gauge valve No. 12 in the open model showed the Gaussian distribution. That being said, in other pressure gauges such as No. 36, 48 and 60, symmetry pressure coefficients with kurtosis greater than 4 were observed. Regarding the closed model at 90 degrees angle of wind flow, in all 4 pressure valves (No. 12, 36, 48 and 60),

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symmetry distribution and kurtosis higher than 4 were observed. Evidently, in any situation due to the existence of the structure against the wind flow, there was a possibility of forming vortices as well as separation flow; the curves were far from their Gaussian distribution. Thus, these areas should be given more attention for structural design.

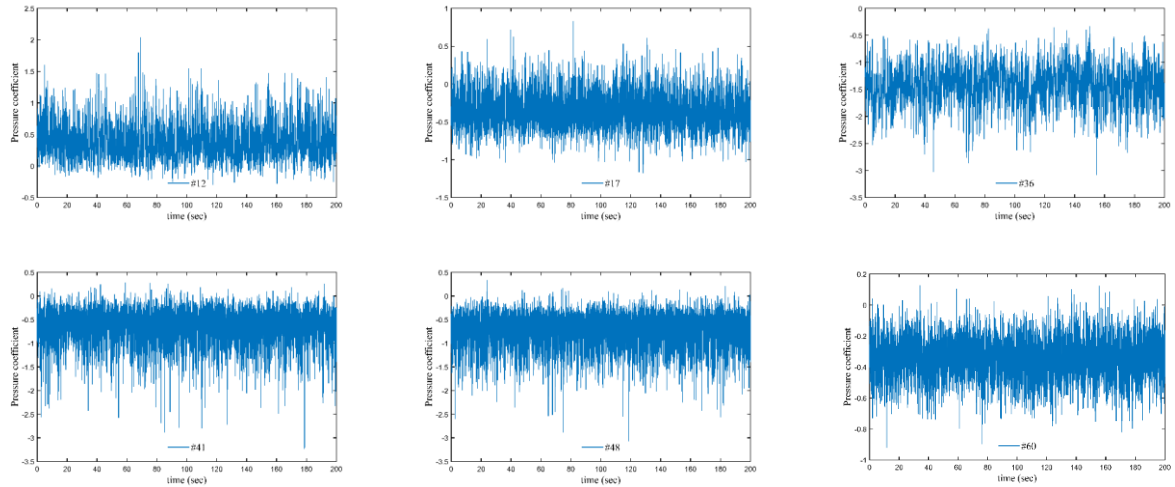


Figure 5-23: Time history of the pressure coefficient at 0 degrees, model MO716

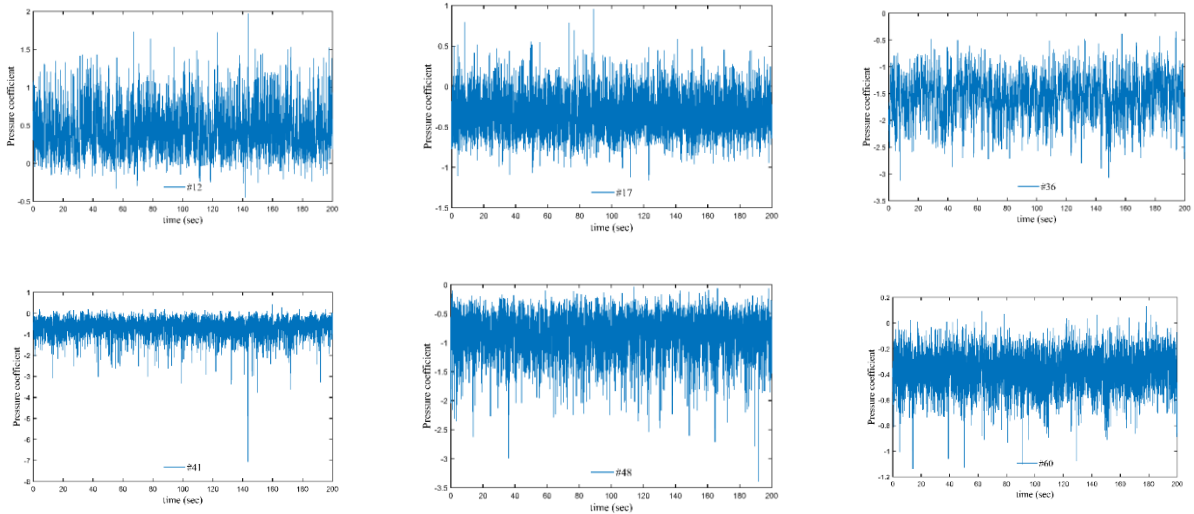


Figure 5-24: Time history of the pressure coefficient at 0 degrees, model MC716

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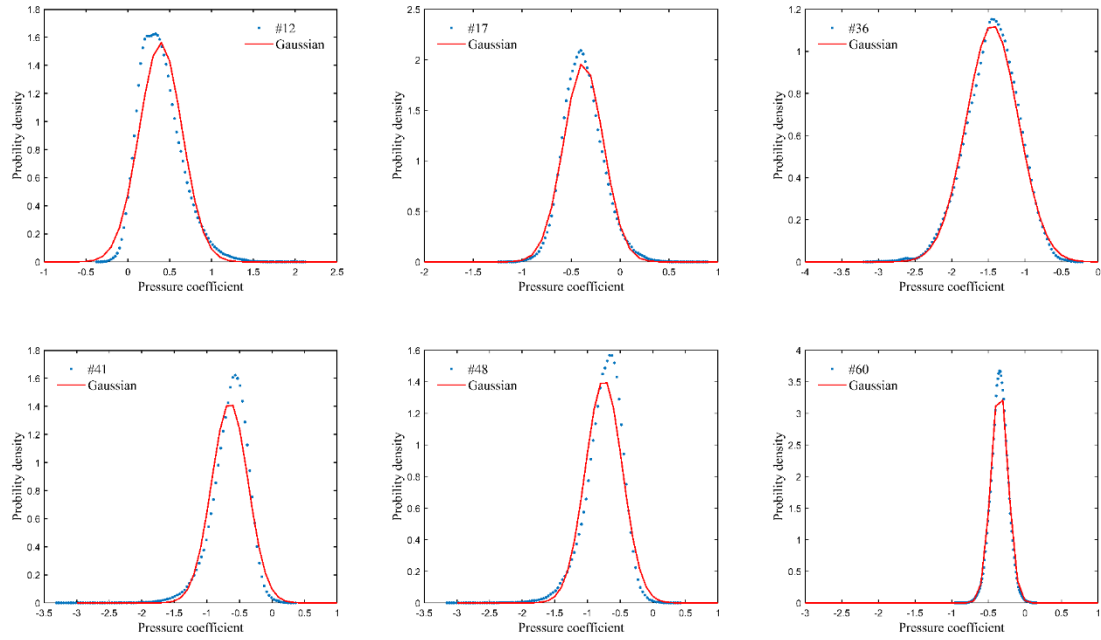


Figure 5-25: The Pressure coefficients PDF at 0 degrees, model MO716

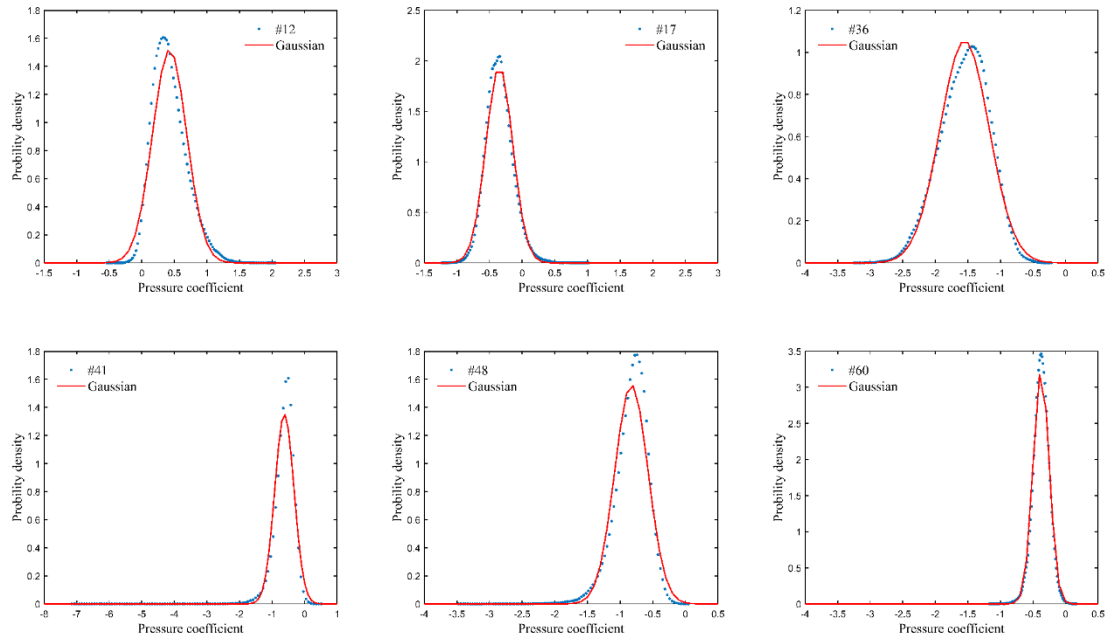


Figure 5-26: The Pressure coefficients PDF at 0 degrees, model MC716

5.2.8. High-Order Statistic Characteristic

To examine the non-Gaussian properties of pressure coefficient, it was essential to use statistically higher parameters such as Skewness and Kurtosis. In this section, according to the pressure measurement in 5 repetitions, the relationship between skewness and kurtosis values regarding the four lines of pressure gauge valves in model's margin (line No. 1, line No. 8, line A and line H) at angles of 0, 30, 60 and 90 degrees was provided for both open and closed models, regarding model 716 mm. Figure 5-27 shows the position of selected lines. According to the estimated results, almost all sensors showed a difference from the normal distribution (Gaussian).

In general, at all angles, pressure gauges placed in front of the wind current showed a positive skewness value of up to 1. In addition, with increasing the absolute value of skewness, kurtosis increased to greater than 3. Negative skewness was mostly observed leeward side and at the structure's sides, especially near entrances (line No. 1 and line No. 8). Larger negative skewness values were more prevalent at diagonal angles. The only exception was in wind flow perpendicular to the span in the open model, which in line No. 1 showed much higher skewness than even diagonal angles. Whereby the thin thickness of the structure against the wind flows was expected to be the reason. Diagrams of skewness variations in relation to kurtosis are provided in Appendix D-9.

The highest non-Gaussian was observed at 90 degrees angle in the open model and at zero and 60 degrees in the closed model. With a change in wind flow angle from zero to 30 degrees in the open model, no significant change was observed. However, changes in the skewness and kurtosis parameters at line No. 1 under the 90 degrees angle of wind flow greatly increased. At 30 degrees angle, the pressure gauge valve No. 56 located at line No. 8 showed different values than the other gauges, which showed non-Gaussian statistics were influential in this area.

At the angle of 60 degrees, pressure gauge valves No. 33 and 57, located in line No. 1, showed the effect of non-Gaussian compared to the other pressure gauge valves, that the impact of the pressure gauge valve 57 in the line H could also be obtained compared

to the other pressure gauge valves. The two pressure gauges, No. 25 and 33, located in the middle, were less affected by non-Gaussian properties at 90 degrees.

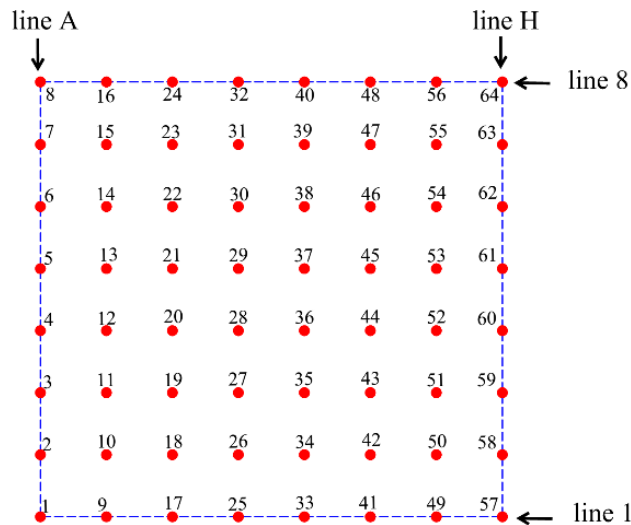


Figure 5-27: Selected lines around the structure

According to Figure 5-28, changes in skewness and kurtosis parameters in the closed model in line No. 1, kurtosis variation was greater and fluctuated all the way from zero to 90 degrees. Maximum changes in skewness were observed at the angle of 60 degrees. Under zero degrees wind flow, the pressure gauge valve No. 41 showed more changes than the other pressure gauges and expressed the effect of non-Gaussian. Non-Gaussian was more noticeable in pressure gauge No. 57 located in line H under 30 degrees wind flow angle. At 60 degrees angle, the non-Gaussian properties in pressure valves No. 1, 9, 17 and 57 were superior to the other pressure valves' positions. Also, at 90 degrees angle, the pressure gauge valves No. 1, 2 and 57, 58 showed different trends in line A and line H.

In both open and closed models, pressure gauges located at the edge of the model, especially on the leeward side or the windward side near the ground, expressed the greatest effect of non-Gaussian.

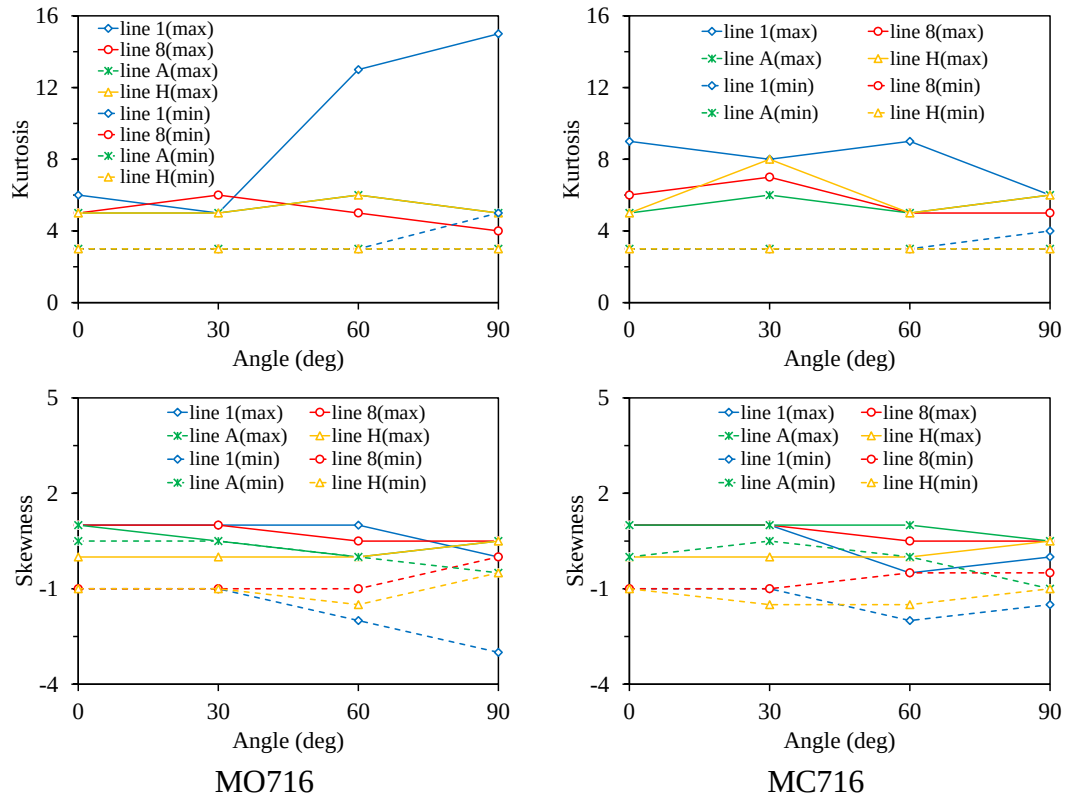


Figure 5-28: Kurtosis and skewness distribution in the interval at two cases for four degrees

5.2.9. Non-Gaussian zoning

The Gaussian standard has a skewness range of $[-0.5, 0.5]$ and a Kurtosis range of $[2.5, 3.5]$. According to the outcomes from kurtosis and skewness values of all pressure gauge valves at four angles of zero, 30, 60 and 90 degrees, the structure's non-Gaussian zoning was defined. The non-Gaussian criterion was considered larger than 4, and the absolute skewness value was considered to be greater than 0.5. Thus, four colours were used to identify the areas. The white colour indicated the Gaussian region, the red colour represented the region when the absolute value of the skewness value was greater than 0.5, blue stood for the region when the kurtosis criterion was greater than 4, and finally, purple indicated when both criteria were consistent with each other. In both open and closed models, there was no definite symmetry regarding the display of non-Gaussian properties. In the open model on the windward side, most areas of the structure were affected by these characteristics. In closed models, more appropriate

symmetry than the open models was observed. In Figure 5-29, in the open model at angles of 30 and 60 degrees, most of the structural parts were subjected to non-Gaussian. Given that at the angle of 90 degrees, these properties' effect could be seen only in the first two lines of pressure valves. However, in the closed model at the angle of 90 degrees, the structure's performance was similar to low-rise buildings, thus in most parts of the structure, the effect of non-Gaussian was observed (Figure 5-30). Knowing the Gaussian and non-Gaussian areas in the structure will help designers to have a better understanding of building and the areas which require more care over design procedure.

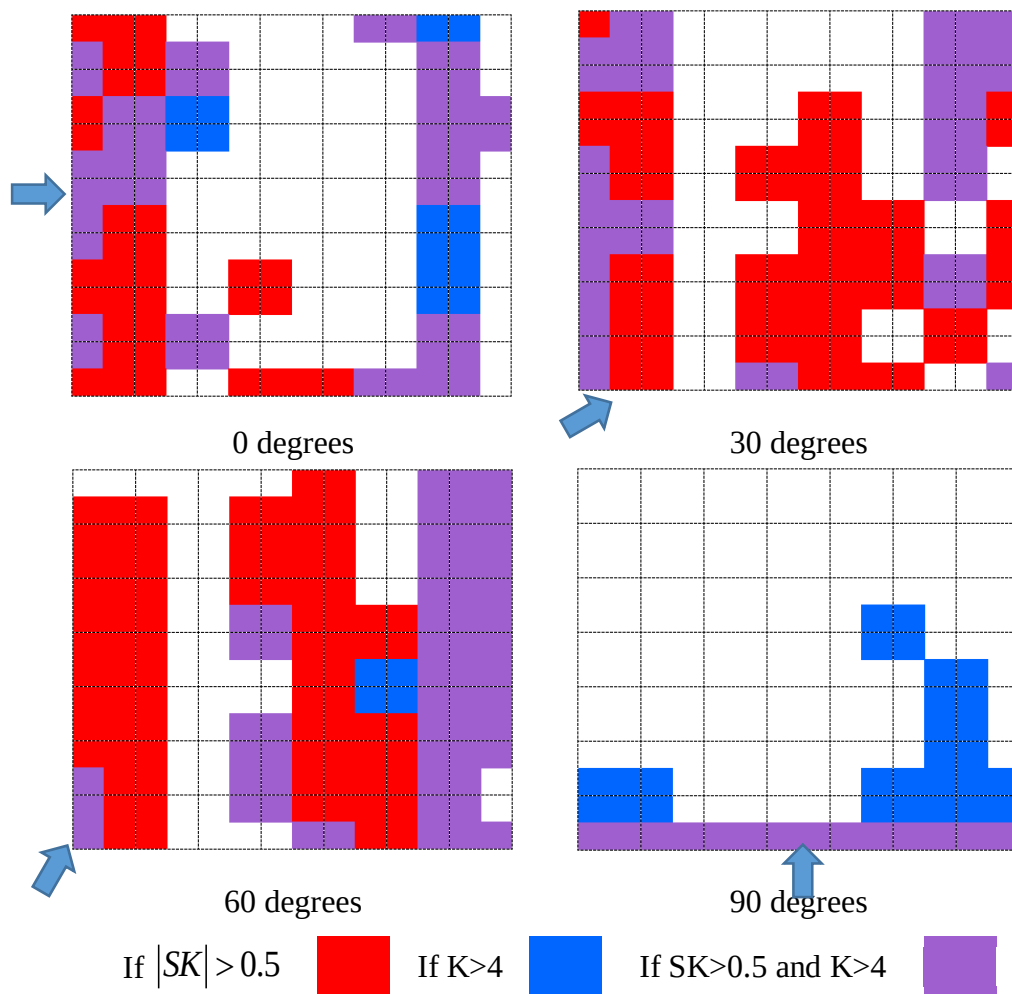


Figure 5-29: Non-Gaussian zoning on open model at four degrees

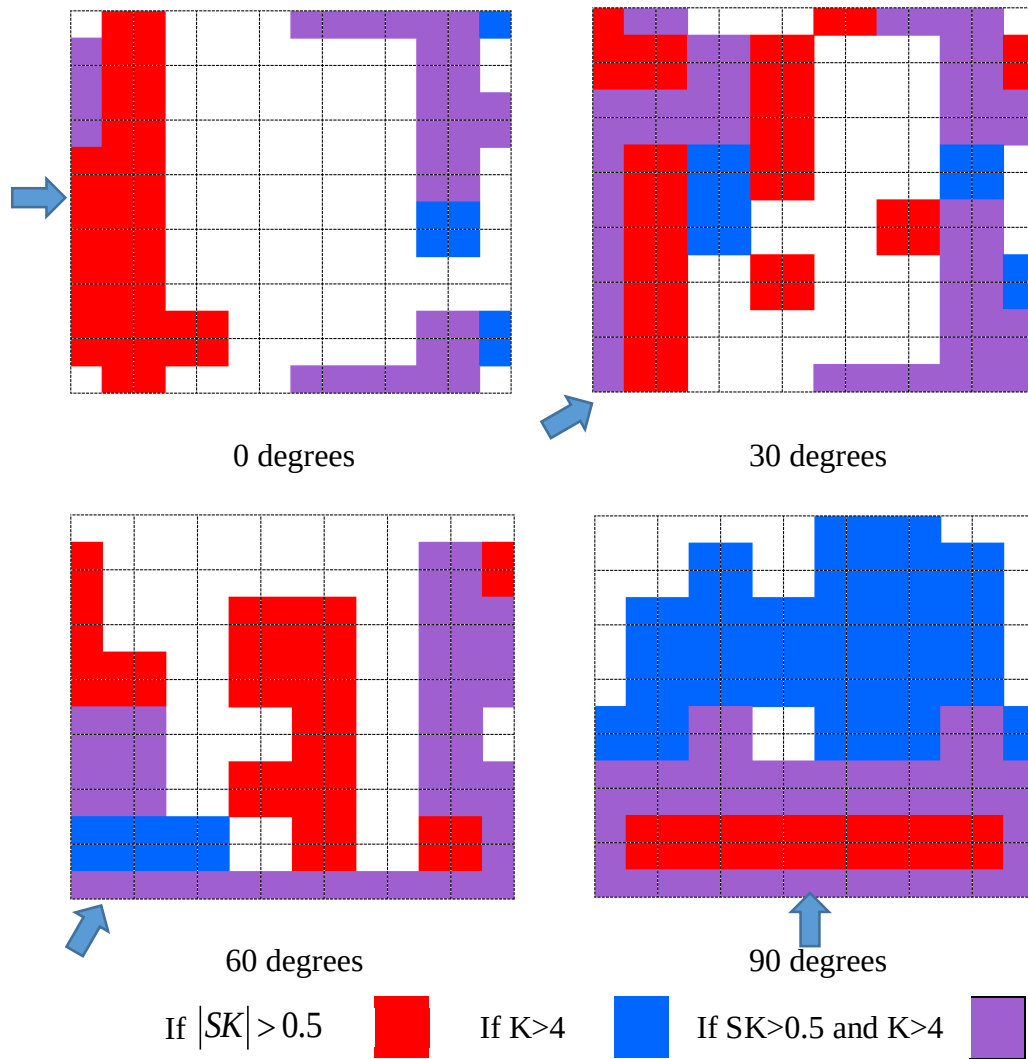


Figure 5-30: Non-Gaussian zoning on closed model at four degrees

5.2.10. Closed models

With advancing in building sector and rapidly growing new designs, any design is appreciated. The main purpose of this section was to present two various types of closing planes and investigate their behaviour under wind load. Two closed models with thin and thick closer panels were investigated and results were discussed in this section.

In the open models, as the angle of wind flow increased, suction at the top of the structure decreased, and the greatest suction occurred in the b_L area, attributed to the current distribution and separation flow phenomenon. The same trend was observed in both closed models. Approaching the 90 degrees angle, similar to low-rise structures, suction was seen at the edge of the models due to the separation flow phenomenon (Figure 5-31).

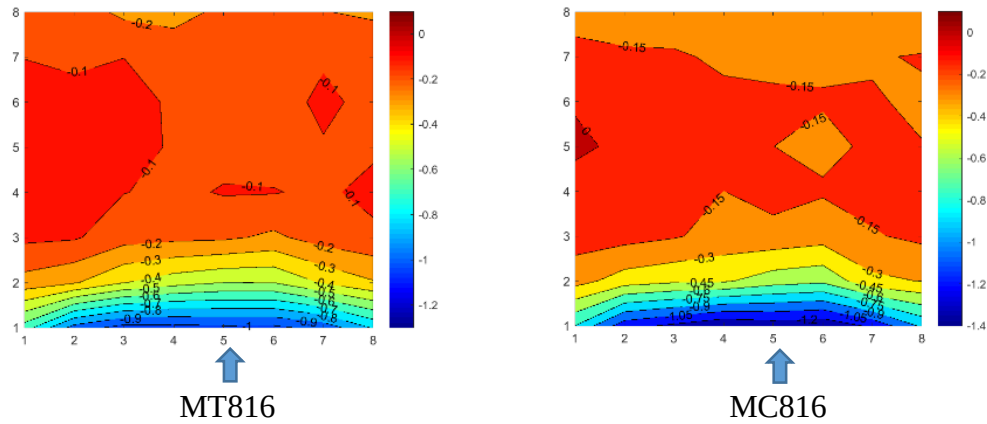


Figure 5-31: Mean pressure coefficient at 90 degrees angle under 6 m/s velocity

Figure 5-32 presents a comparison of the mean pressure coefficients at 90 degrees angle. As observed, suction on the external surface of both models was almost the same. Under 4 m/s velocity, pressure distribution in both models was slightly irregular. While the pressure coefficient values in MT716 and MT816 were equal in both windward and leeward areas near the ground. The pressure coefficient in the mid part of the model varied from model to model, and fluctuation was illustrated in both models. Under 10 m/s velocity, pressure coefficient in MT816 model was lower than MT716 model. This trend could be seen at the crown, and the value of the pressure coefficient in the models became more alike and are almost the same in most parts of the leeward area.

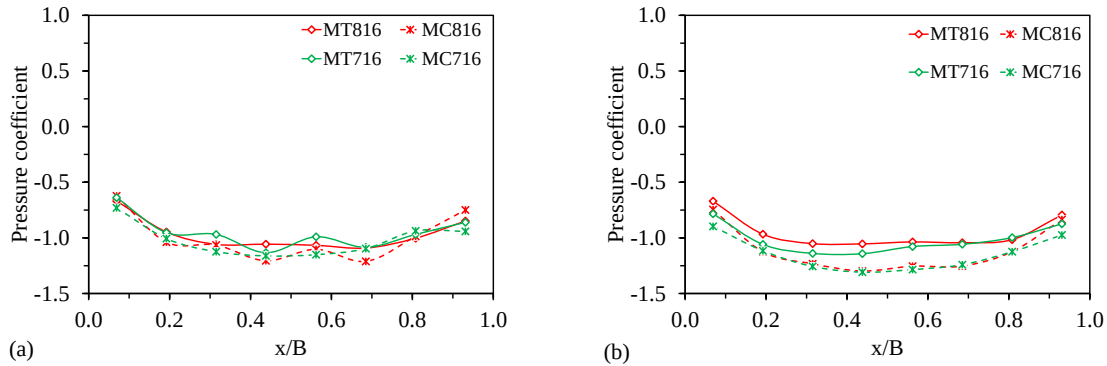


Figure 5-32: Mean pressure coefficient at the edge of structure (line No. 1) under angle 90 degrees a) 4 m/s velocity b) 10 m/s velocity

Suction created in closed model with thick closure panels was less than closed model with thin closure panels. By investigating the mean pressure coefficient in line No. 4, significant difference was not observed between both closed models at the velocities of 4 m/s and 10 m/s. It was also observed, that suction obtained at the model's crown in closed model with thin closure panels was always slightly higher than closed models with thick closure panels. The pressure coefficient created in the windward area in the 816 mm model was less than 716 mm model under both 4 m/s and 10 m/s velocities. Also, suction created at the top part of the model, in 716 mm model was greater than the 816 mm model, while the difference in pressure created behind the models was slight. As illustrated in Figure 5-33, under 4 m/s wind velocity, pressure coefficient distribution in windward area was slightly different between both 716 mm models and was almost equal at the top of the structures. This trend was completely reversed in 816 mm models. Situation under 10 m/s wind flow velocity was slightly different compared to 4 m/s wind velocity. Pressure distribution on the windward area was almost the same in both models, while difference in pressure distribution was observable at the top part of the model. It should be underlined that the pressure coefficient in closed model with thick closure panels was less in most parts of model compare to a model with thin closure panels. It was also observed that the suction obtained at the model's crown in closed model with thin closure panels was always more than the closed model with thick closure panels. This difference in the 816 mm model under 10 m/s velocity was greater than the other models.

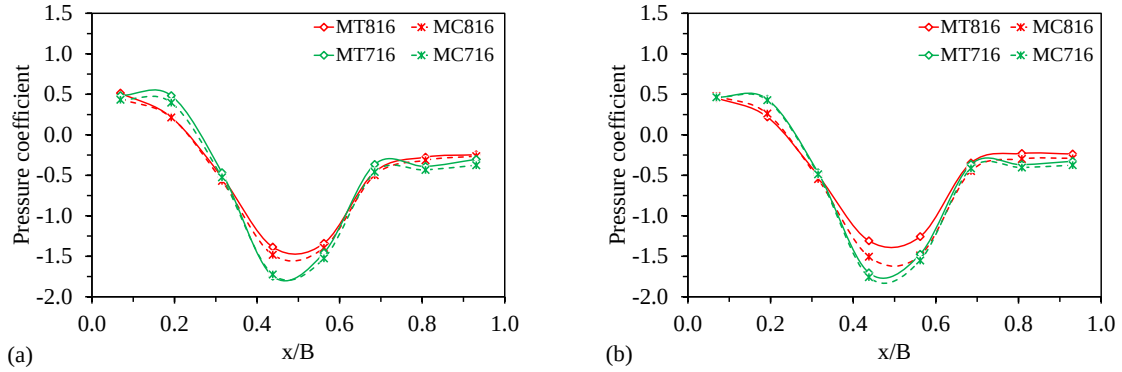


Figure 5-33: Pressure coefficients for the midline (No. 4) in both open and closed span models at 0 degrees a) 4 m/s velocity b) 10 m/s velocity

Results obtained from model 716 mm in two lines of No. 1 and 8 at 30 and 60 degrees are presented in Figure 5-34 and Figure 5-35. Suction created in most parts of the closed model with thick closure panels was lower than the closed model with thin closure panels. It was observed that the general behaviour was almost the same in both closed models and the maximum and minimum pressure and suction occurred in similar areas in both models.

Under 30 degrees wind flow at both 4 m/s and 10 m/s velocities, pressure coefficient was almost the same in the windward area in lines No. 1 and 4. However, at the peak and leeward area, the pressure coefficient was different between models, and the maximum difference appeared at the top of the models in line No. 4 (Figure 5-34). The maximum difference in pressure coefficient between models in windward area was obtained in line No. 8 under 4 m/s velocity and in leeward area in line No.1 under 10 m/s velocity. Regarding suction created at the top of the models, it can be observed that the suction created in both models occurred almost at the same locations. Under 60 degrees wind flow, pressure coefficient distribution at 10 m/s velocity had a more regular pattern in comparison with pressure coefficient distribution at 4 m/s velocity. Maximum difference in pressure coefficient between models occurred precisely in the same areas and lines, under 30 degrees angle wind flow.

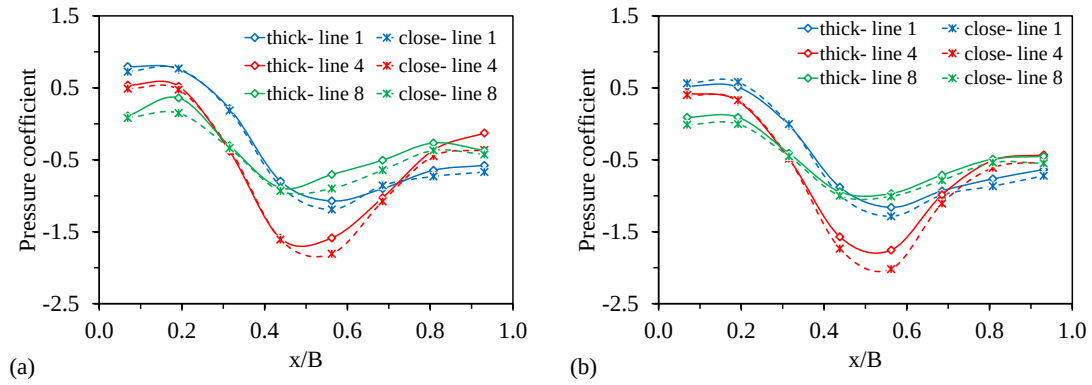


Figure 5-34: Pressure coefficients in 716 mm models at 30 degrees wind flow angle

a) 4 m/s velocity b) 10 m/s velocity

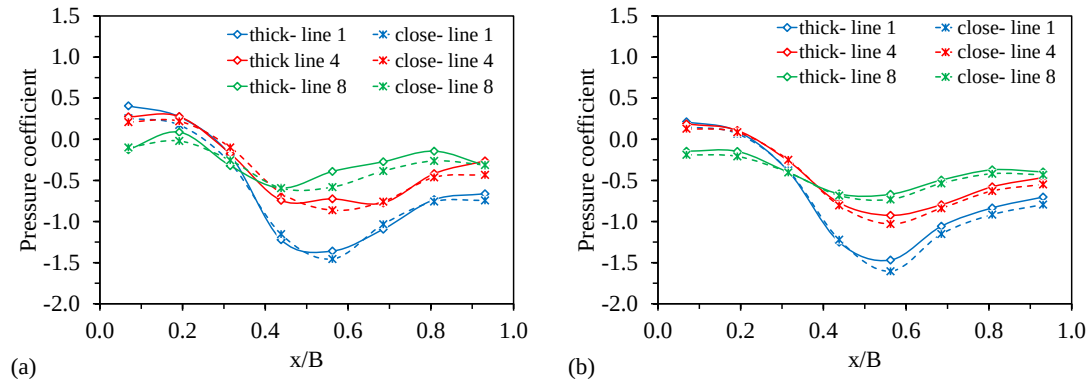


Figure 5-35: Pressure coefficients in 716 mm models at 60 degrees wind flow angle

a) 4 m/s velocity b) 10 m/s velocity

The pressure coefficient in model 816 mm, same as model 716 mm, showed the values obtained from the closed model with thick closure panels were less than values obtained in closed model with thin closure panels. Under 30 degrees wind flow, line No. 4 (located at the middle of the model) at both 4 m/s and 10 m/s velocities had the most difference in pressure distribution between two closed models. While pressure coefficient distribution in line No. 8 had the most adjustment in both models. Maximum differences in pressure coefficient occurred at the models' crown. These differences were observed more under the velocity of 10 m/s at 60 degrees wind flow, and line No. 8 had the closet adjustment between both models, same as 30 degrees wind flow.

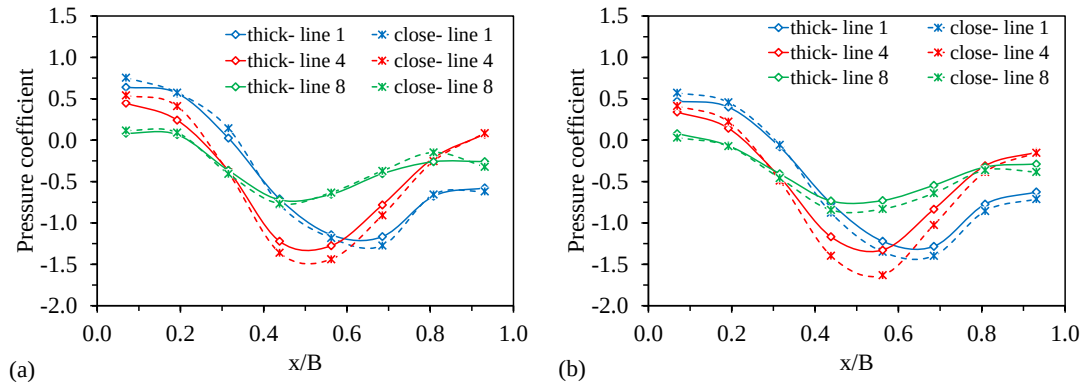


Figure 5-36: Pressure coefficients in 816 mm models at 30 degrees wind flow angle

a) 4 m/s velocity b) 10 m/s velocity

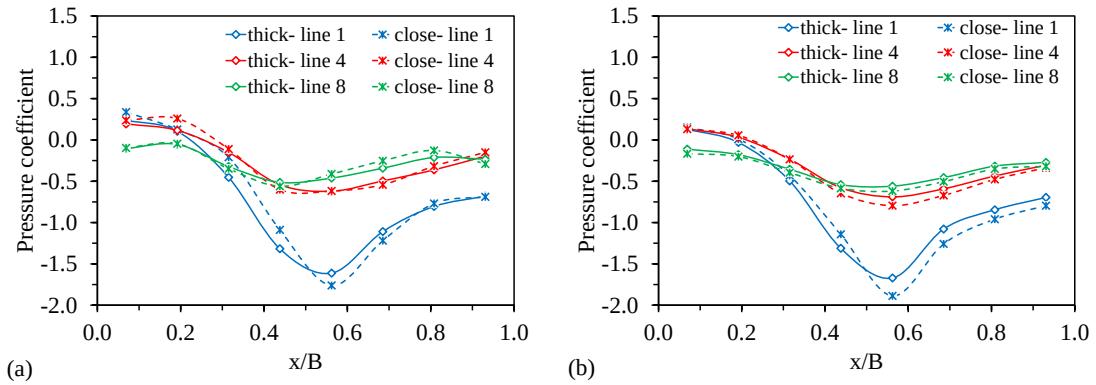


Figure 5-37: Pressure coefficients in 816 mm models at 60 degrees wind flow angle

a) 4 m/s velocity b) 10 m/s velocity

Pressure coefficient distribution along the lateral direction under wind flow perpendicular to the opening (90 degrees) is presented in Figure 5-38. The ratio $y/D = 0.04$ represented closer edge to the wind flow (line No. 1), and the ratio $y/D = 0.95$ indicated the farther edge to the wind. In general, pressure distribution in both closed models had a regular trend relative to each other. In both models, maximum suction was created at the edge of the models. In closed model with thick closure panels under 4 m/s velocity, there was a slight difference in pressure coefficient in low ratios, while in higher ratios more differences observed between models. This trend was vice versa at 10 m/s velocity, that a difference in pressure coefficient was observed in low ratios, while in high ratios the pressure was very close to each other.

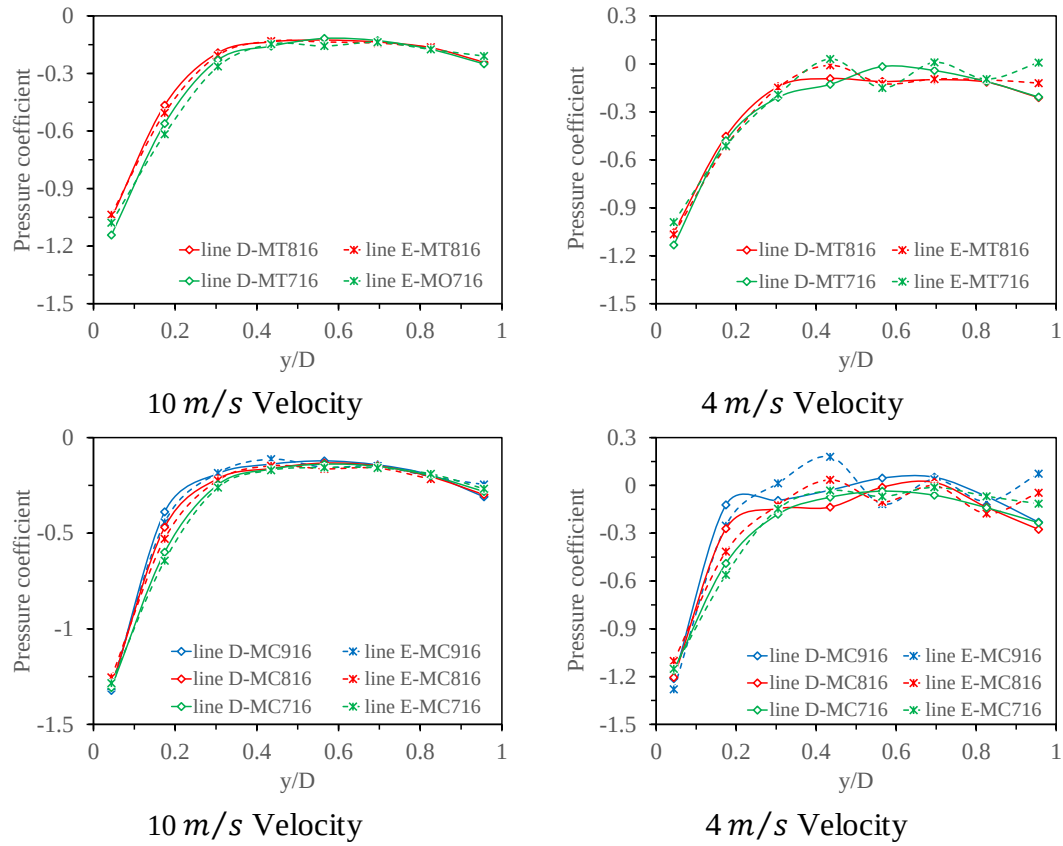


Figure 5-38: Pressure coefficients under the angle of 90 degrees in both closed models

Generally, it could be observed that both models had similar trend in pressure distributions, while some differences still were notable such as suction created at the models' crown and pressure coefficient which were greater in models with thin closure panels. Meanwhile closed bending active model with thick closer panels, due to their behaviour facing lateral force were recommended. In conclusion both models are suitable for design and construction depending on the design preferences.

5.3. Numerical modelling

5.3.1. Introduction

The use of CFD is introduced as one of the methods for investigating wind flow effect on structures. The numerical model's crucial point is the implementation validation of performed simulation according to the experimental wind tunnels.

Using ANSYS software as one of the simulation tools in CFD, wind effect on bending active structure was investigated in this section. To numerically investigate the active bending structure, rigid and flexible models were simulated. The aim of modelling was to compare and verify the pressure coefficient created on the surface of the structure obtained from modelling with wind tunnel laboratory data. Each model was discussed separately in all the steps of the modelling process. As mentioned in the previous section, in the wind tunnel laboratory, models were built using GFRP material.

5.3.2. Rigid modelling

In this clause, the process of modelling a rigid model using active bending form-finded model was reviewed in detail. In the process of numerical modelling, the choice of the computational domain, mesh type and size, and boundary conditions must be selected reasonably in order to achieve the desired result. The RANS method in ANSYS fluent software was chosen for the simulation. According to the wind tunnel test performed on the active bending model, numerical modelling for the rigid model was designed. Open 716 mm model was chosen for numerical modelling. The model specifications used in numerical modelling are presented in Table 5-3.

Table 5-3: Wind tunnel model characteristic

Model	Span (mm)	Height (mm)	Depth (mm)	Thickness (mm)	f/L	Air temperature (°C)	Air Density (kg/m^3)	Viscosity ($kg/m-s$)
MO716	703.3	308.3	910	3.1	0.44	29	1.1687	$1.863e^{-5}$

Rigid modelling results

Considering the wind direction parallel to the span of the structure (0 degrees wind flow angle), the windward face was subjected to positive pressure. After that, due to the structure's blockage (obstacle) in the wind flow direction, the flow lines moved to the structure's top. Therefore, by the formation of flow lines based on the shape of the structure (change in flow lines pattern), negative pressure coefficient (suction) occurred in the outer surface of the model. The maximum negative pressure coefficient was

recorded at the top of the structure due to the separation flow phenomena. In the following, the fluid flow, recirculation region, and vortexes were created. The vortexes, which were located in structure's leeward generated negative pressure coefficient; it is essential to note that this negative pressure was much lower than the top of the structure.

Changes in the flow lines in the windward area (with respect to the structure height and disruption in the wind flow) and the leeward area (with respect to the fluid flow separation near to the top of the structure) are presented in Figure 5-39. Flow lines in contact with the structure at the end of the $t=2$ sec are shown in Figure 5-40.

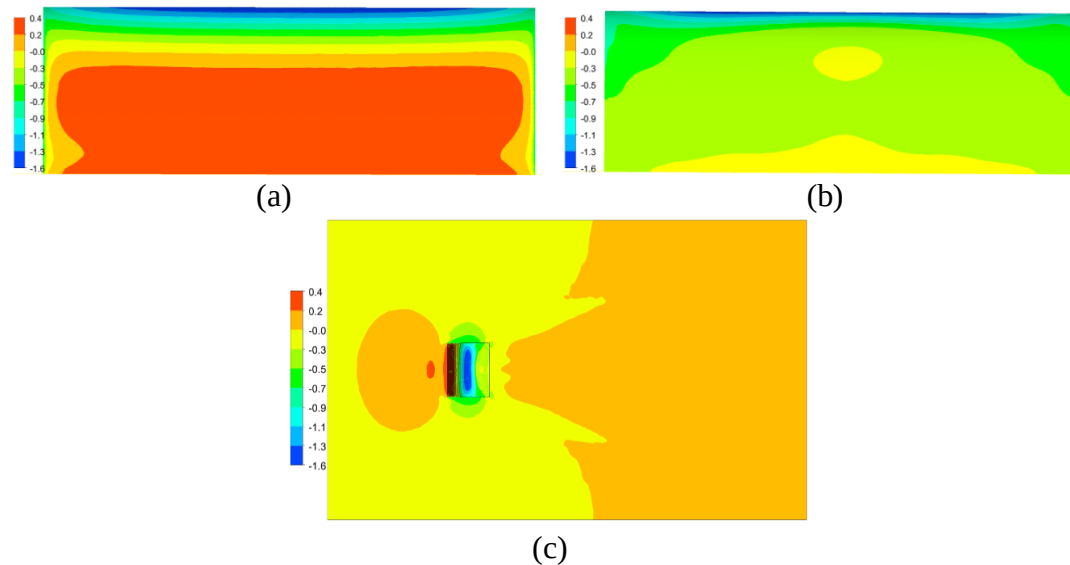


Figure 5-39: MO716 Pressure coefficients control a) windward area, b) leeward area, c) plan

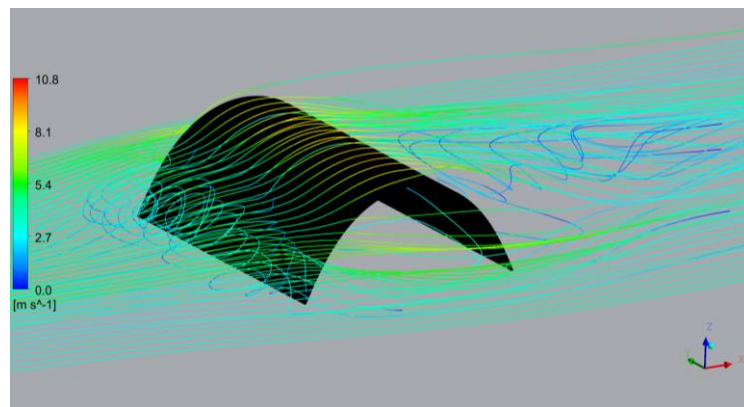


Figure 5-40: Flowlines in model MO716 ($t=2$ sec)

To compare between numerical and experimental outcomes, the average pressure coefficient for lines No. 1, 4 and 8 are shown in Figure 5-41. These lines introduced flow in the structure's input section (lines No. 1 and 8) and middle section (line No. 4). These lines were considered in the location of the tap pressures in the laboratory model. The pressure coefficient on these lines was plotted that L introduced the structure's span length, and x was the longitudinal coordinates for each tap pressure.

Results obtained from numerical modelling for both lines, No. 1 and 8 were almost equal with results obtained from wind tunnel testing. However, results obtained from the midline (line No. 4), both on the windward side and the top of the structure, were less than results obtained from laboratory tests, and only in the leeward area results were close with each other. Numerical results for lines No. 1 and 8 showed a good compatibility with the laboratory results in the windward and leeward sides, and only at the top section of the structure, numerical results expressed lower pressure coefficients than the experimental findings. Numerical results on the windward side showed that the difference in pressure values between the middle lines and the inputs was minor, while in the wind tunnel laboratory results, this difference was significant. In general, the numerical model's pressure coefficient values were lower than the laboratory results. This difference was especially noticeable at the top part of the model, which experienced higher suction.

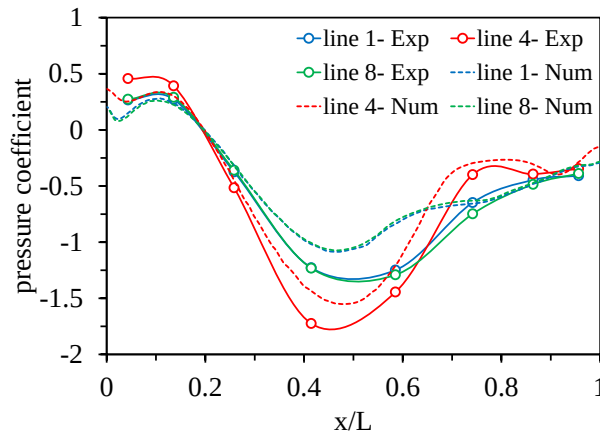


Figure 5-41: Pressure coefficient related to tap pressures located on lines No. 1, 4, 8, for model MO716

5.3.3. Flexible Model

In this section, numerical simulation of bending active structure was performed by considering dynamic behaviour. Bending active structures are considered as lightweight structures, which tends to vibrate against the wind flow. Therefore, their dynamic behaviour against wind flow is a critical issue. Consequently, fluid structure interaction (FSI) was used for estimating the dynamic behaviour according to numerical simulation. Since monolithic models were computationally inefficient when applied to computational wind engineering (CWE) problems, a partitioned coupling scheme was adopted in this work. In the following, the numerical analysis results were discussed, including the structure's pressure and displacement magnitudes.

Flexible 716mm model was simulated using the wind tunnel testing specifications. Model's characteristics and material properties are showed in Table 5-3 and Table 5-4, respectively.

Table 5-4: Material properties

GFRP	Poisson's Ratio	Young's Modulus (Pa)	Density (kg/m^3)
	1723.56	$1.7e^{10}$	0.28

5.3.3.1. Flexible modelling results

The pressure coefficient contours in 2 second duration are shown in Figure 5-42. In the fixable modelling, the windward face was subjected to positive pressure and at the top of the model, high suction was applied due to separation flow. Also, negative pressure occurred on the leeward due to the vortex creation. However, this negative pressure was much lower than the negative pressure at the top of the model. Flow lines in contact with the model at the end of the $t=2$ sec are shown in Figure 5-43. Similar to the rigid modelling, changes in the flow lines, in the windward (with respect to the model's height and disruption in the wind flow) and in the leeward (with the respect of the fluid flow separation near the top of the structure) were seen.

In order to better comparing with wind tunnel experimental results, pressure gauge's locations in the wind tunnel testing (Figure 5-44) were chosen as the desired locations

for displacement measurement. Figure 5-45 and Figure 5-46 present the displacement in two tap pressures of No. 17 and 41 in X and Z directions. Displacement created at the top of the structure (the area between tap pressures No. 32 and 25) in X and Z directions were equal to $10\ \mu m$ and $8\ \mu m$. The deformations at the top of model were recorded less than deformations at the edge of the model (tap pressures No. 41 and 17). Meanwhile, this difference in Z direction was significant; therefore, it could be said that the model would not have many elevation changes. Deformation in X direction caused by pressure in windward area and suction in leeward area led to the structural vibrations and elevation changes.

During the simulation, the displacement in X direction for the tap pressure No. 17 and 41, was in the positive direction, while the displacement in Z direction, at the tap pressure No. 17 was in the negative direction (downwards), on the other hand this change in the tap pressure No. 41 was positive and led to increasing height. Displacements at all points had the same trend, while in the Z direction were depended on the point's location, based on locating in windward or leeward side.

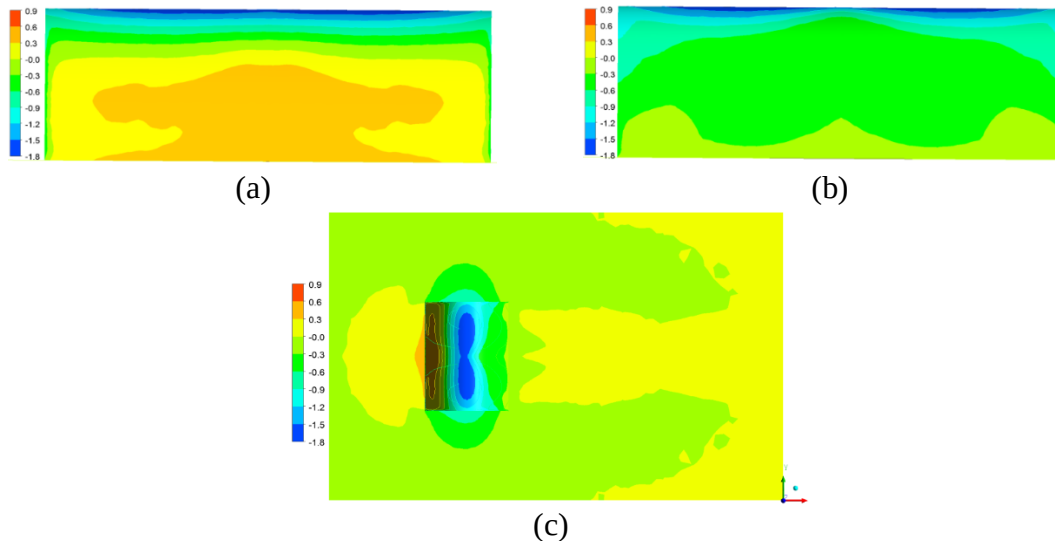


Figure 5-42: MO716 pressure coefficients contours, a) windward area, b) leeward area and c) plan

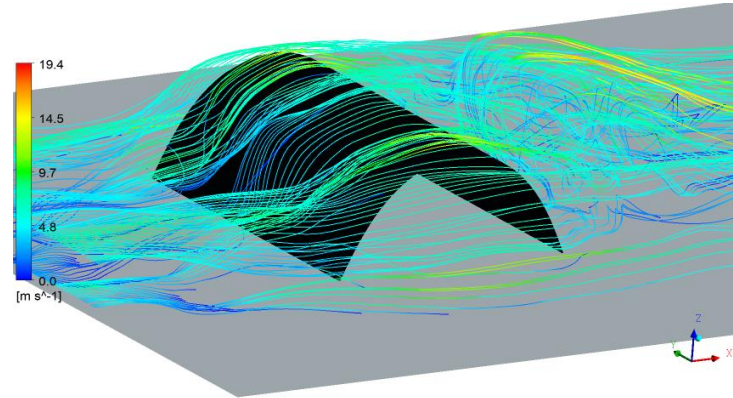


Figure 5-43: Flowlines in structure model MO716 (t=2 sec)

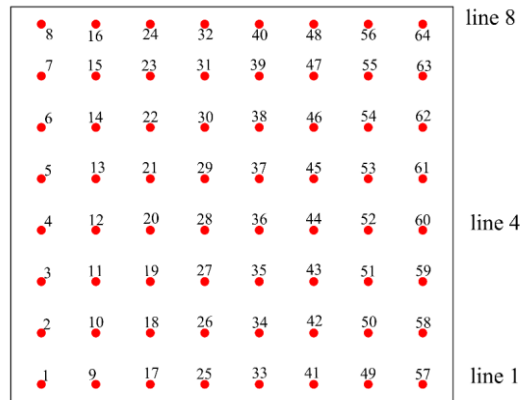


Figure 5-44: Pressure gauge valves locations in the wind tunnel

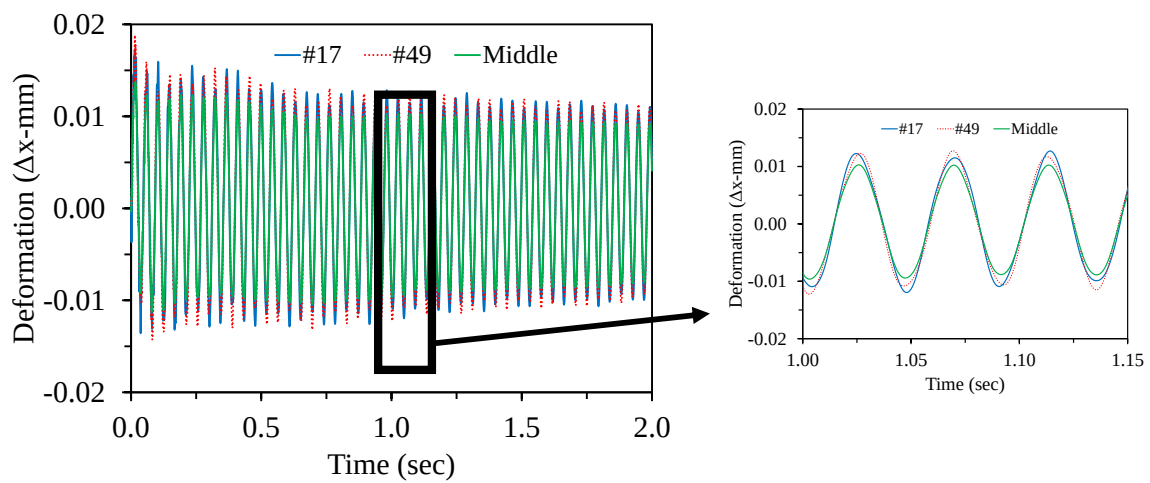


Figure 5-45: Structure's deformation in two desired points, in the X direction

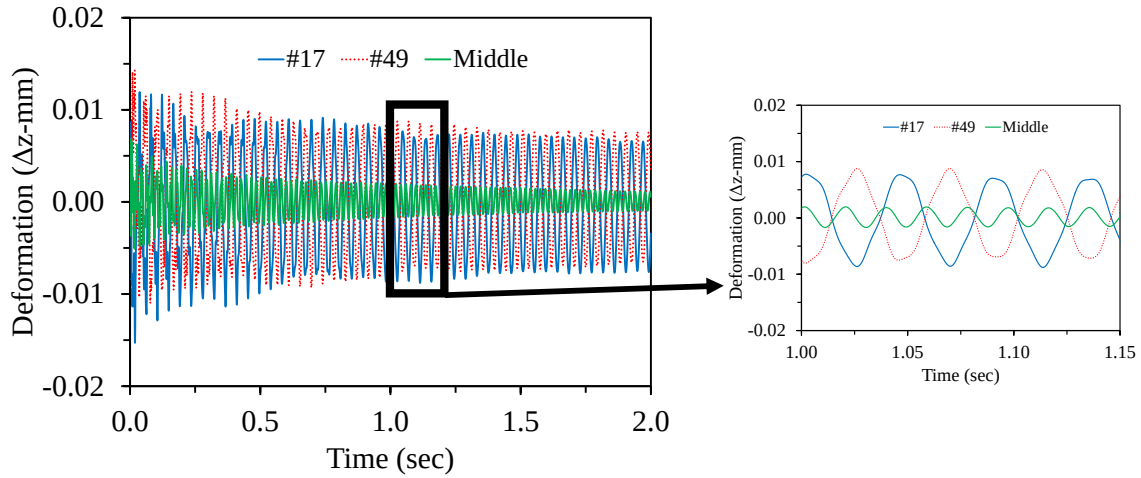


Figure 5-46: Structure's deformation in two desired points, in the Z direction

Numerical and experimental mean pressure coefficients for lines No. 1, 4 and 8 are shown in Figure 5-47. Generally, an acceptable agreement between flexible numerical modelling and experimental results was observed. The outcomes had a excellent match in windward area in both lines No. 1 and 8. The main difference in pressure distribution between numerical and experimental outcomes captured at the middle line (No. 4) at the top of the structure, however this discrepancy lied within an acceptable range. Therefore, it could be indicated that the model in the wind tunnel test was performed flexibly. It suggested that in numerical simulations the flexible model can be used for further investigations in future work.

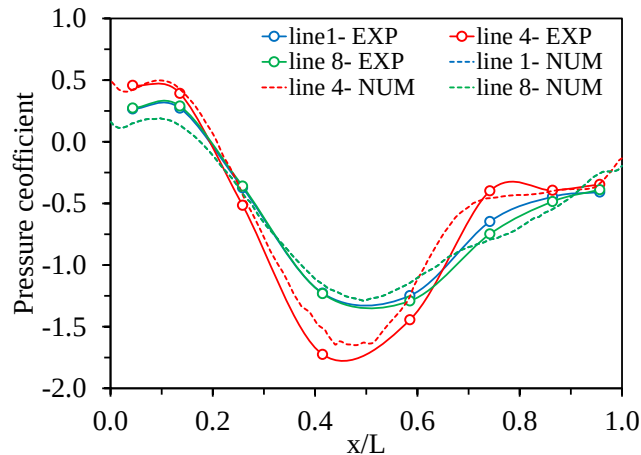


Figure 5-47: Lines No. 1 & 4 pressure coefficient, for model MO716

5.3.4. Summary

Numerical modelling is an alternative method to analyse structures under wind loading. Therefore, the use of CFD methods is one of the useful methods in this field. Laboratory tests due to various reasons such as time and cost have not always been recommended. Verified numerical modelling with laboratory tests allows engineers to simulate structures reliably.

In this study, to better understand the behaviour of bending active structures, numerical modelling was carried out in rigid and flexible models. Results obtained from each method were compared separately with laboratory outcomes. Rigid modelling results showed a discrepancy with laboratory results, while results obtained from flexible modelling were more in conformity with laboratory outcomes. Based on the results obtained, the pressure values from flexible modelling were more homologous with laboratory outcomes than the pressure values from the simulated rigid model. Also, as flexible modelling mode gives the ability to study more details such as structural deformation, using this method can provide more accurate results of the active bending structures behaviour.

5.4. Conclusion

Wind load is one of the important parameters in the stability analysis and structural behaviour study. The effects of lateral force on light and flexible structures, are important due to low damping and high deformation. Accordingly, the form-finded active bending structures with different f/L ratios were examined to investigate the effect of wind flow around these structures. GFRP materials were used in this study in consequence of their suitability for bending active formations. Elementary stresses were created in the models due to initial bending, which play an essential role in bending active structural behaviour. In this study, models tested in the wind tunnel laboratory were examined in open and closed modes, and the pressure distribution was studied. The most important findings of wind tunnel laboratory of bending active models were presented in the following.

- It was observed that each part of the model facing the wind flow was under positive pressure and the opposite side was under suction. The geometric asymmetry in the distribution of pressure coefficients in the non-Gaussian property distribution section was also shown with respect to the zero degrees angle.
- Velocity changes in the Reynolds number had no significant effect. However, at low velocities (e.g., 4 m/s), scattering of the mean pressure coefficients was greater, due to its flexibility allowed in the structure. As the wind velocity increased, the fluctuations in the structure were limited and the model was exposed to the flow with more rigid performance.
- In closed models, the structure behaved similarly to expectations of low-rise buildings. Under the wind flow perpendicular to the span (90 degrees angle), the structure was subjected to negative pressure, and the highest suction was observed at the top of the models, meanwhile in open models under the same current, due to the thin thickness of structure facing the flow, the pressure distribution values were very limited. The pressure distribution had greatly reduced by adjusting the flow angles from parallel to perpendicular to the span in open structures. Yet, in closed models, this reduction was not significant.
- With increasing the height and the f/L ratio, in the windward side near the ground, a rotating area was formed. This rotating area, also known as the horseshoe vortex area in dome structures, was observable in 716mm model's windward side.
- The maximum suction applied to the structures in 360 degrees was achieved at certain angles of wind flow. In open models, maximum suction occurred closer to 90 degrees angle by increasing the f/L Ratio. However, in closed models, the maximum suction was observed at a lower angle in comparison with the angle obtained from the open models. In the $f/L = 0.44$ ratio both open and closed models expressed similar critical angle. It can also be concluded that the pressure distribution on the models depended on the structure's height. In closed models

with $f/L = 0.22$ and 0.33 ratios, maximum pressure was recorded in a local area in a specific pressure gauge valve, and other areas did not show a significant amount of pressure.

- Under the parallel flow to the span, maximum suction was created at the top of the models, in the presence of separation flow was. However, by changing the flow direction, maximum suction's position on the structure shifted from the top of the model to the span's edge, so that under the flow perpendicular to the span, only the span's edge undergone significant changes in mean pressure coefficients. Changing wind flow angle caused the change in positive pressure location in the models. Also, increase in suction near each pressure gauge valve at different angles indicated the occurrence of separation flow near the intended pressure gauge. Under the wind flow parallel to the span, the pressure coefficient distribution in both open and closed models did not differ from each other. While under other flow directions, due to the side panels' presence in the closed models, the pressure coefficients in line No. 1, especially in the leeward area, showed a significant difference. It should be bear in mind that with the increase in the structure's height, this difference between open and closed models was limited. In other words, more bending provided more resistance in contrast to the wind flow.
- Under parallel flow to the span with increasing f/L ratio, maximum suction's position changed from the top of the models towards the windward area. It can also be stated that the separation flow occurred in the leeward area in all models. Maximum suction in Models 716 mm and 816 mm had the same position, and it occurred closer to the middle of the models. In addition, in model 916 mm, its position was closer to the edge of the models.
- According to the statistical parameters and evaluation of non-gaussian characteristics in the 716 mm model, it was found that in places where separation flow and vortex formation occurred, non-Gaussian characteristics were more

observed. At oblique angles, the effect of non-Gaussian was observed in most parts of the model.

- In closed 716 mm model under 90 degrees wind flow, non-Gaussian area was observed in most part of the model. While in open models, this effect was observed more at the edge of the model. The behaviour of open and closed models at the angle of 90 degrees was very different from each other due to the models' thin thickness and closure panel.
- The pressure and suction trend was observed the same in both closed (thin and thick closure panels) models. However, the pressure coefficient in the closed model with a thick closure panels was lower. This difference was greater at higher velocities.

After performing laboratory testing in the wind tunnel, numerical simulations were performed in ANSYS software in rigid and flexible modes. In rigid numerical modelling, due to the non-application of structural features, the pressure coefficients obtained were lower than the laboratory values. However, simulating the flexible model showed a good correspondence with the laboratory results. It suggested that the flexible mode can be employed for further investigations in more complex structures.

CHAPTER 6

MOCK-UP

This chapter propose a self-support structure using active bending theory. First, the methods used in the new design are described and then a full-scale model constructed. Finally, numerical modelling has been the full-scale run-on model to investigate the structural behaviour.

6. Mock-up

6.1. Introduction

Within recent years the bending active theory has gained significant attention, largely due to the advancement in technologies relating to the use, design and construction of lightweight structures. Consequently, introducing the application of this theory in the construction of new structures has been one of the main challenges. Therefore, in this chapter, an attempt was made to introduce a structure using the findings from laboratory tests and numerical modelling. An arrangement of the members was proposed to examine the self-stability of the formed structure.

6.2. Self-supporting structure

Elastic energy stored inside the members due to bending active could be used in different ways in structural engineering. One way is using internal energy created in members to design and construct structures with self-supporting capability.

In this chapter, using the obtained findings, a design was created and presented. GFRPs with low modulus of elasticity and high yield stress are the suitable material in bending active applications, and thus, were used to demonstrate the proposed design. The horizontal rectangular cross-section was selected for the application of initial bending, which allows large deformations for the members and produces reasonable internal stresses. According to the results, f/L ratios less than 0.7 were recommended as a better performance could be achieved in the application of bending and loading. Therefore, the f/L ratio of 0.5 was used in the construction of the proposed design.

6.2.1. Fundamentals of self-supporting structures

The main concept of the presented structure consisted of two strips. By creating the appropriate deformation and locating the members in the desired positions, the internal forces created in the structure due to bending were sufficient for the external stability of the structure, which suggested that external forces were no longer required.

The initial state consisted of two strips with equal size placed on top of each other with a joint at each end (Figure 6-1). By sliding two members away from each other with the presence of joints at each end, the members started to exert forces and the initial bending was created. As a result of sliding strips from each other, a loop shape was created by reaching a 180 degrees angle between strips. By locating the strips in the final desired position, internal forces created in both members were neutralized, and the structure was placed in a stable position without any external force required.

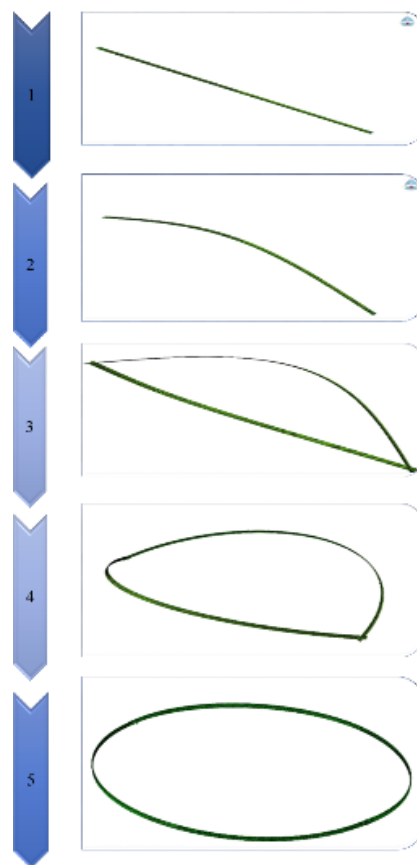


Figure 6-1: Deformation steps

6.2.2. Investigation of Various Parameter effects on Interaction and Internal Forces

In the following, the model consisting of two strips was studied to consider various factors that affect the internal forces. As the strips were situated in the final desired

position (loop shape), stresses were created in the strip as well as the pins. Due to the creation of interaction between strips, the internal forces eliminated each other, and the model stabilized itself. At the interaction points between strips, the stresses created in the outer strip were slightly less than the stresses created in the inner strip. The outer strip was only restricted at the location of the pins, and the very end part of the member could move freely away from the inner strip. While in the inner strip considering the end part which was in contact with the outer strip was restricted. This caused a various stress distribution in the two strips. The interaction and forces created in the strips could be attributed to various parameters. Therefore, various parameters listed as below were studied to investigate the interaction between the strips under different conditions.

- Various modulus of elasticity of the materials
- Various geometries and dimensions
- Pins size and location

Accordingly, nine models were considered to investigate the effect of mentioned parameters. Model No. 1 was considered to be the main model with a modulus of elasticity of 17 GPa, length of 6 m, width of 80 mm, and thickness of 8 mm. In order to investigate the various parameters, some changes were made based on Model No. 1 to form the rest of the models. Table 6-1 presents the specifications of the created models.

Model No. 2 with 30 GPa modulus of elasticity was designed to investigate the effect of various modulus of elasticity on the model's behaviour. In Model No. 3, the strip's thickness increased to 20 mm. Model No. 4 and 5 with 60 mm and 160 mm widths were designed to investigate the effect of changes in width on the model's interaction. In Model No. 6, the pin's head diameter size increased to 40 mm and in Model No. 7 to 80 mm. Models No. 8 and 9 investigated the effect pin's location on interaction distribution. In model No. 8, pins were positioned 120 mm from each edge, and in model No. 9, they were 40 mm away from the edge.

Table 6-1: Models' characteristics

Model's number	Modulus of elasticity (MPa)	Thickness (mm)	Width (mm)	Pin diameter (mm)	Pin's centre distance from the end edge of the strip (mm)	Length (m)
1	17	8	80	20	80	6
2	30	8	80	20	80	6
3	17	20	80	20	80	6
4	17	8	60	20	80	6
5	17	8	160	20	80	6
6	17	8	80	40	80	6
7	17	8	80	80	80	6
8	17	8	80	20	120	6
9	17	8	80	20	40	6

The models consisted of two strips and after deformation and creating a bending active loop, one strip was located at 180 degrees angle and the other at 0 degrees angle which the strip at 0 degrees was the outer member.

6.2.2.1. Results

In this section, the results of the mentioned models are presented. For this purpose, dimensions as well as the maximum and minimum stresses created at the arc's crown of models were examined. In the following, results are presented in Table 6-2.

Table 6-2: Models' results

Model's number	External distance in the longitudinal direction (mm)	External direction in the latitudinal direction (mm)	Maximum principal stress at 0 degrees strips (MPa)	Maximum principal stress at 180 degrees strips (MPa)
1	3727.7	3722.0	36.72	37.20
			-37.03	-37.52
2	3728.0	3721.8	64.76	65.65
			-65.31	-66.22
3	3734.3	3733.1	85.68	87.49
			-86.44	-88.29
4	3726.8	3722.5	36.72	37.30
			-36.94	-37.53
5	3706.6	3735.5	17.26	17.36
			-19.91	-20.05
6	3727.0	3722.6	37.11	37.63
			-37.04	-37.49
7	3717.2	3728.1	37.24	37.69
			-37.16	-37.59
8	3668.26	3676.17	37.34	38.17
			-37.65	-38.12
9	3763.56	3781.6	18.58	18.80
			-18.41	-18.61

As mentioned, Model No. 1 was used as the main model and in the other models by making the desired changes the effects of changes on the geometry and stress created were investigated. Stress distribution for Model No. 1 is illustrated in Figure 6-2, and stress distribution for other models is presented in Appendix E. As deformation was applied to the model, it created bent strips and internal stresses increased in members especially in the middle of members. Stress created appeared as tensile stress in the outer side of the members and compressive stress in the inner side. As shown in Figure 6-3 and Figure 6-4, the stress variations were obtained near the pins. Due to the neutralisation of forces created in the members, an excellent structural stability was achieved without the need of external forces. The results showed that the dimensions of the members in both X and Y directions were almost equal, creating an oval shape (almost a circular shape). Also, the stresses at the arc's crowns in both strips were close, and small difference was seen due to the strips' positions.

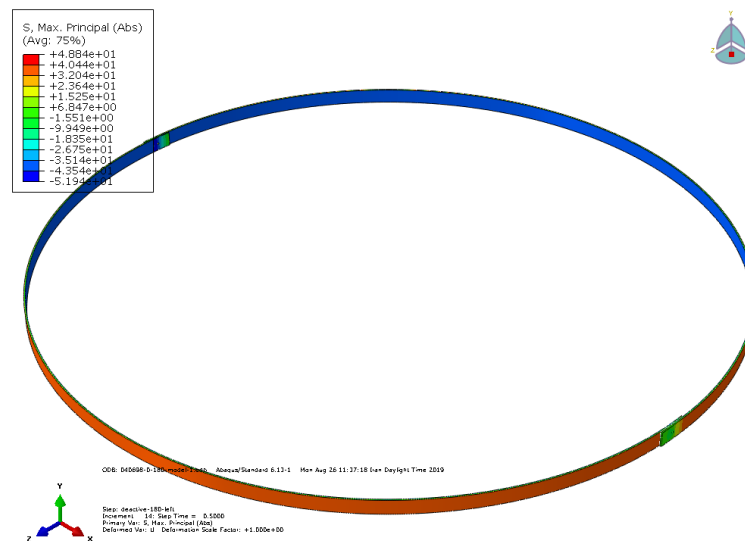


Figure 6-2: Stress distribution in Model No. 1

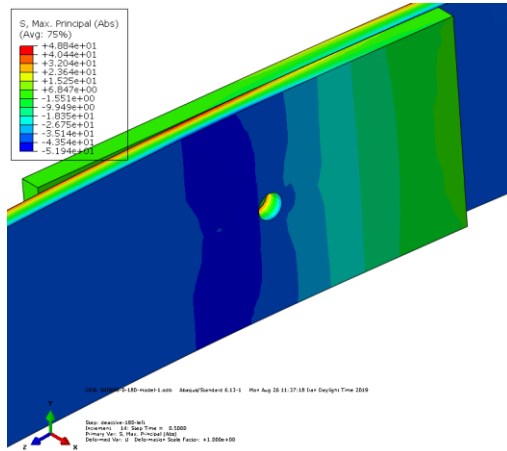


Figure 6-3: Stress distribution in the left support zone, Model No. 1

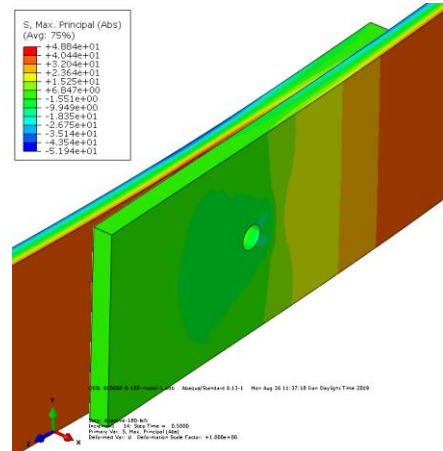


Figure 6-4: Stress distribution in the right support zone, Model No. 1

The general geometrical shape of the model was not varied with the changes in the modulus of elasticity in Model No. 2. However, as the modulus of elasticity increased, the stresses created at all parts of the strips increased; therefore, it should be noted that for each design, appropriate materials should be selected to keep the stresses in the elastic range. Model No. 3 showed that the model's general geometry was not varied with increasing strip's thickness. On the other hand, the stress in the arc's crown increased in both strips. In Model No. 4, the model's general geometric shape was not changed much with increasing the strip's width to 60 mm. Also, the stress created at the crown of the strips was not significantly different from the Model No. 1. In Model No. 5, the strips' width was increased to 160 mm, which caused slight changes in the model's geometry, and the stress decreased throughout the strips. In Models No. 6 and 7, increase in the diameter of pins' head created slight changes in the geometry and stresses. In Model No. 8, the pins' locations were changed to 120 mm from the edge, which slightly affected the model's geometry but the internal stress remained almost constant. In Model No. 9, the pins were located 40 mm from the edge. As a result, the contact length of the two strips was reduced which, in turn, reduced the stress created at the structural interaction point. It could be noted that using Model No. 1's

configuration, more reasonable outcomes could be attained with the comparison of the outcomes from the other created models.

6.2.3. Self-supporting Deployable Bending Active Structure

In the following, an attempt was made to design and construct a self-supporting deployable bending active structure using the attained findings. The GFRP materials, horizontal rectangular cross-section, and f/L ratio of 0.5 were chosen due to their performance. Also, Model No. 1's configuration from Table 6-1 showed an acceptable output during the numerical modelling. Therefore, it was employed as a base of the self-supporting deployable bending active structure in this study.

Adding extra members to the base brought the shape closer to the practical structure. In the first attempt, three members were allocated for the new design. By applying an initial bend and sliding members on top of each other, the strips began to angle, and both ends started to move towards each other. As the members were located at the three angles of 0, 90, and 180 degrees, the geometry became close to the dome shape as presented in Figure 6-5(a). Increasing the numbers of members to 5 provided a better stability in the design (Figure 6-5(b)). Based on the findings, a structure with seven members was proposed to design and construct a self-supporting deployable bending active structure (Figure 6-5(c)). After applying the initial bend, the strips were located at the angles of 0, 30, 60, 90, 120, 150 and 180 degrees, respectively. When the strips were placed in their final position, they were in symmetrical positions, except for the strip located at a 90 degrees angle. The interactions created in the strips neutralized the stresses created, and as a result, the structure became completely stable.

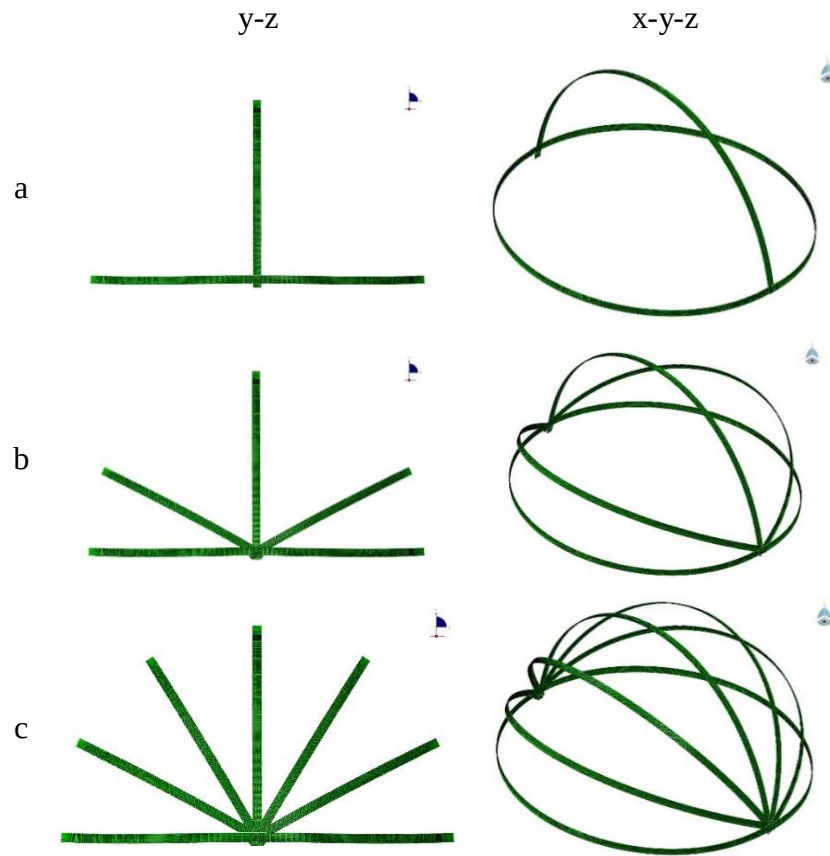


Figure 6-5: Mock-up

To better understand the structural behaviour of the models presented, numerical modelling for the proposed structure was carried out by *ABAQUS* software. The stresses and deformations created in the models were measured and further investigated. As presented in Figure 6-6, maximum stress was created near joints in the strips located at the angles of 0 and 180 degrees. Also, high tension was observed in the mid part of the members (the arc's crown).

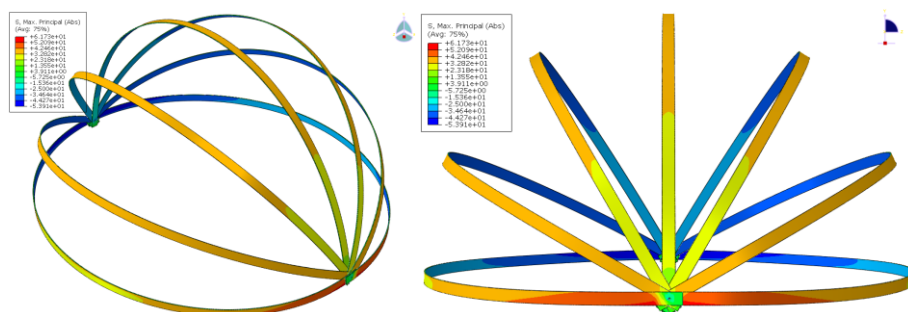


Figure 6-6: Stress distribution

Figure 6-7 illustrates stress distribution at the middle of strips. As demonstrated, in all strips the upper part was under tension and on the contrary the bottom part was experienced compression.

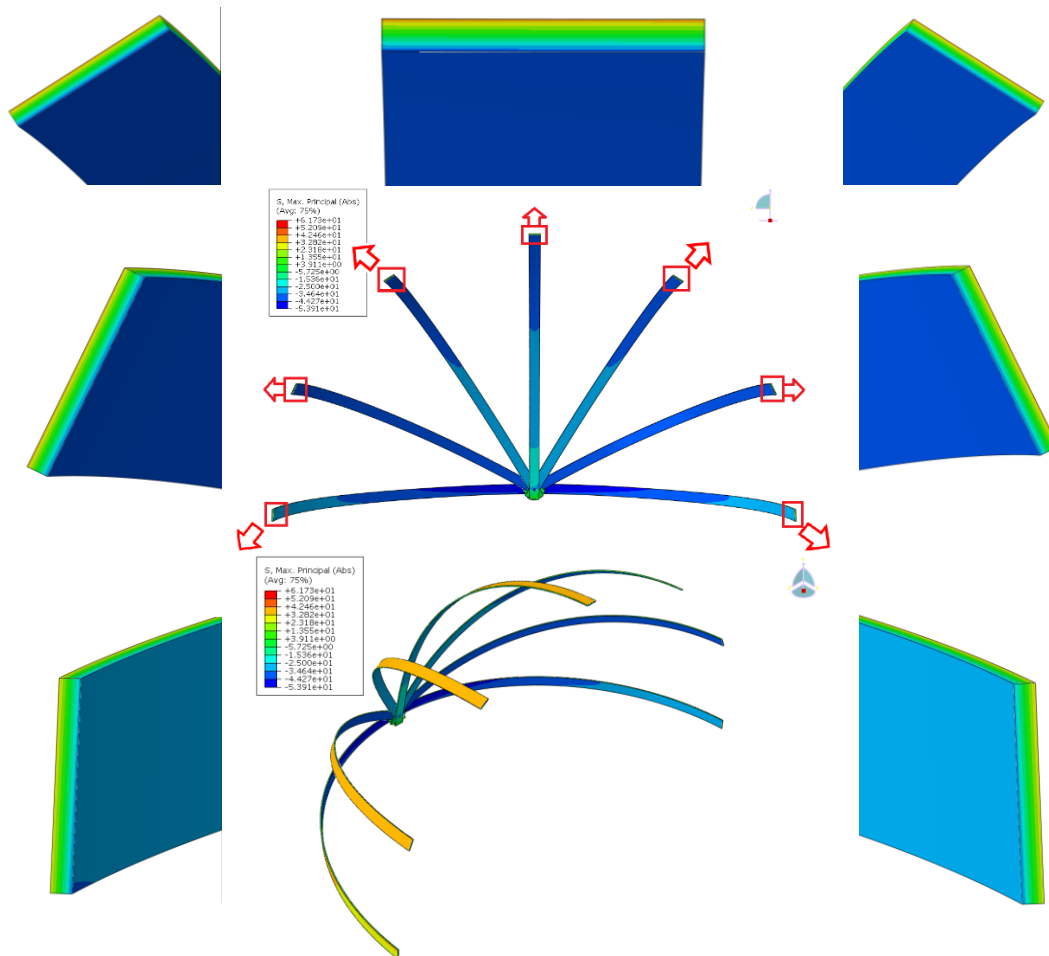


Figure 6-7: Stress distribution in the middle section of each strip (zy cut (x-plane) - perspective)

The created physical self-supporting deployable bending active structure is shown in Figure 6-8. It was set on the meadow in the Department of Architecture and Built Environment at the University of Nottingham for two months to investigate the performance of the structure under outdoor environment. A membrane was used to cover the structure for a better appearance (Figure 6-9).



Figure 6-8: Self-supporting Deployable Bending Active Structure



Figure 6-9: Self-supporting Deployable Bending Active Structure in operation

6.2.4. Conclusion

Based on the results from previous chapters, a structure was proposed with the consideration of the findings. Specifically, glass fibre reinforced polymers with low modulus of elasticity and high yield stress, horizontal rectangular cross section, and the f/L ratio of 0.5 were chosen to construct the proposed structure. Based on the final outcomes from the constructed structure, it was observed that feasibility and stability were achieved, which proved the reliability of the findings. Lightness, speed of construction, portability and installation of structures without the need for skilled staff or sophisticated technology, and multipurpose uses are among the features of the structures provided.

This structure also has a unique feature of self-stability that stress created in the model's members interact with each other in a way which provide stability without the need for external supports. Also, this structure showed the intelligent side of bending active theory, which flat members could achieve a 3D structural shape with the ability of reversing back to their original shape without any permanent deformations caused and external support required.

CHAPTER 7

CONCLUSION, LIMITATION AND FUTURE WORK

This chapter presents a general overview of the results.

7. Conclusion, Limitation and future work

7.1. Introduction

The use of new technologies in temporary and lightweight structures is rapidly increasing. Accordingly, adequate knowledge of the materials' behaviour used and the factors affecting their design is crucial for the further development of this type of structures. This study investigated the effects of load distribution, geometry, temperature, and wind loads on the structural performance of bending active structures and provided a better understanding of the impact on the architectural and engineering design. The research was based on the extensive use of experimental tests and numerical simulations and provided valuable resources to architects and engineers supporting the design and manufacturing of lightweight bending active structures.

7.2. Experimental Tests

7.2.1. Structural Tests

Experiments including bending, loading, and tensile tests and tests designed to understand the effect of temperature were conducted to investigate the structural behaviour of bending active members and material performance.

In bending experiments, by applying displacement to the joints, initial bending was created, and the value of the axial strains was computed at the desired locations using strain gauges. From the analysis of the experimental results obtained imposing a displacement, it indicated that:

- After applying the displacement to the supports, the models were subjected to the stress resulted from bending. The upper web was subjected to tensile stress, and the lower web was under compression stress.
- The strain values in the strain gauges, which were symmetrically positioned, were equal and compatible with the level of accuracy of the experimental tests.

- By applying a point load at the arc's crown, the stress distribution changed in the samples. By increasing point loading, the strain values decreased at the crown and increased throughout the sides. In the case of increasing point loading to a certain extent, the strain at the crown in the upper web varied from positive to negative and conversely in the lower web. Therefore, the upper web moved from the tensile zone and entered the compression zone. This was evident in the modified laboratory and numerical models.
- Unloading returned the strain to the original value. It could be deduced that the materials' behaviour was within the elastic range as required in bending active theory.

To investigate structural behaviour and load-bearing of the samples that undergone temperature loading, bending and external loading were examined. With the application of temperature loading, the materials became more brittle. Resulting in sample failure during the loading procedure. This reflected the effects of temperature on the elastic behaviour of materials. With reducing the elastic behaviour of materials, the reversibility of bending active members was affected, and this may disrupt their function.

To investigate the effect of temperature on material's characteristics, tensile testing was performed. Temperature loading was applied using climatic chambers to investigate the effect of specified set temperature and cycling temperature changes. Results obtained from temperature loading indicated that the GFRP materials' behaviour and resistance parameters were influenced by temperature loading. In the case of a single target temperature change, the modulus of elasticity and yield stress had not changed significantly. However, cyclical temperature changes made the material more brittle, and the range of elastic behaviour decreased, with major implications on the design of bending active structures. As the behaviour of bending active structures is defined only in the elastic range, therefore, by increasing the modulus of elasticity and decreasing the yield stress of materials, the stress created in the structure could increase and the structure could enter the plastic range via less

stress. Therefore, this becomes a key aspect to be considered in the design and manufacturing of bending active structures.

7.2.2. Wind tunnel tests

Lateral forces applied to the structure are one of the important parameters in the stability analysis and structural behaviour study. The effect of lateral forces was studied through wind tunnel testing on a scale model. To investigate the effect of wind flow around the structure, open and closed modes of bending active models were employed. The tests were carried out over 360 degrees with incremental steps of 15 degrees.

The wind tunnel tests provided valuable experimental results which gave a better insight of the interaction between wind and bending active structures. It was observed that each part of the structure facing the wind flow was under positive pressure and the opposite side was under suction. At low velocities, the scattering of the mean pressure coefficients was greater. Up to the velocity of 4 m/s, fluctuations in flexibility were allowed in the structure. However, with the increase in speed, these fluctuations in the structure were limited, and the models were exposed to the wind flow with more rigid performance.

In the closed models, the structure behaved similarly to a short-rise building. Under the wind flow perpendicular to the span, the models were subjected to negative pressure, and the highest suction was observed at the top of the models. While in the open models under the same current, due to the low thickness of the structure facing the flow, the pressure distribution was very limited. With raising the f/L ratio, a rotating area was formed in the windward side near the ground, which is also known as the horseshoe vortex area in domed structures.

According to the statistical parameters and evaluation of non-*Gaussian* characteristics in the 716 mm model, it was found that in the places where the separation flow and vortex formation occurred around the model, non- *Gaussian* characteristics were observed frequently.

The trend of pressure and suction distribution was observed the same on both closed models. However, the pressure coefficients in the closed model with thick closure panels were lower. This difference was greater at higher flow velocities.

7.3. Numerical modelling

Numerical modelling was used in conjunction with physical models due to laboratory limitations. Based on the experimental tests, the physical models were simulated to explore structural behaviour and the effect of wind.

7.3.1. Structural behaviour

The numerical simulations were initially calibrated with the experimental outcomes and then used to investigate the key factors using ABAQUS software. Material's characteristics played a significant role in bending active structures. A high modulus of elasticity increased rigidity in the models. This increase in stiffness was clearly seen both in the created initial bending and displacement under point loading. Overcoming the materials' yield stress point causes permanent (plastic) deformation, which contradicts the initial assumptions of bending active structures. For this reason, materials with a low modulus of elasticity and high yield stress must be used in the bending active structures to avoid reaching the yield stress point during initial bending and external loading.

From assessing the effect of different cross-sections in bending active structures, it can be concluded that the geometric shape of the cross-sections had a great impact on the stress created in the structure while it had a slight effect on the f/L ratio. Apart from the cross-section, the orientation and angle of the component to which bending was applied significantly affected the level of stress created.

Various f/L ratios affected the models' geometry. At low f/L ratios (up to about 0.7), with the increase in the ratio, the initial stress created in the model increased. However, in the sample with the f/L ratio greater than 0.7, less initial stress was

developed during bending. A high f/L ratio could increase the deformations, and let the structures approach an unstable state.

Distributed load perpendicular to the sample made the crown move upwards. The magnitude of the load did not directly affect the displacement, while the load distribution had a direct effect on the displacement. With the centralization of the applied load, the maximum stress created moved further away from the crown. In the case that stresses created due to loading were in contrast with the initial stress, the overall stress in the structural components decreased. On the contrary, if the stresses created due to external loading and initial bending were aligned, the stress could approach the material's yield stress point, and as a result, it was possible to overcome the yield stress point and led to occurrence of plastic deformations.

7.3.2. The effect of wind

After performing laboratory testing in a wind tunnel, numerical simulation was performed in ANSYS software investigating rigid and flexible models and the results were compared with experimental data. Results obtained from the rigid model showed some discrepancies with laboratory results, while results from flexible modelling illustrated a good correspondence with the laboratory results.

7.4. Mock-up

After having a better understanding of the investigated structural factors according to the laboratory tests and numerical simulation outcomes, an attempt was made to propose a new design. This design was introduced to test the knowledge developed and investigate the challenges faced in the manufacturing of the bending active structure made of GFRP structural profiles. The design was a full-scale model of a self-supporting structure which showed the potential of a structure without the need of external supports to stabilise the structure which was also fully reversible to its original shape. Lightness, speed of construction, ease of installation without sophisticated technology, and multipurpose uses were among the features of the design provided.

Also, this structure shows the intelligent side of bending active theory, which flat elements could achieve a 3D structural shape with the ability of reversing back to their original shape without any permanent deformations caused and external support required.

7.5. Research Limitations

To examine the relevant factors and better understand the structural behaviour of bending active structures, laboratory experiments are required. This study made wide use of physical tests carried out in the laboratories of the Faculty of Engineering of the University of Nottingham. To attain the most accurate results, the laboratory tests of the real-scale model is necessary; however, due to the restrictions such as expenses, space availability, time allocation, and equipment in the laboratories, physical tests were limited on the real-scale models. Therefore, numerical modelling was carried out to validate the outcomes through physical tests conducted on smaller, more practical, and cost-effective samples. However, despite the best efforts to minimize the impact on the research outcomes, further research is recommended on large/real structures and case studies outside the scope of this study.

In addition to examine the structural behaviour of bending active models, the laboratory experiments investigated the effects of temperature on bending active structures' performance. This was done by conducting various temperature loading experiments on GFRP samples. The experimental activity included the application of temperature loading in a realistic range of temperatures. However, the time required for each cycle, costs associated and the limits in size restricted the possibility to assess larger samples, extreme temperatures, and long-term effects.

The wind interaction is considered a crucial load case for lightweight structures, and the investigation of a new structural theory and models in the presence of the wind flow are required. Wind tunnel testing is a reliable technique to investigate the impact of wind on structures and was used in this research. However, the limits of the testing equipment dictated the model's size and the range of wind velocities applied.

7.6. Further Research

This research contributed to the further understanding of the structural behaviour of bending active structures. However, the results opened a set of new research questions which are recommended to researchers approaching them in future. Considering the limitations of this study, the relevant research areas to be investigated are:

- The impact of the geometric scale on the behaviour of bending active structures
- The behaviour of bending active structures in the case of simultaneous application of initial bending and temperature changes
- The behaviour of bending active structures under a higher number of cyclic temperature loadings
- Monitoring of structures at full scale to validate the results obtained on scale models and investigate the effects of large dimensions on the structural performance of materials, profiles, and connections

To investigate the impact of wind on bending active structures, wind tunnel experiments were performed on the bending active structures. Accordingly, the following topics should be considered by researchers approaching the wind engineering challenges associated with bending active structures:

- The effect of barriers and obstacles around the structures
- Internal wind pressure distribution
- The effect of the member's thickness on the aeroelastic behaviour
- To investigate additional meshing alternatives and assess the effect of the mesh dimensions on the results

CHAPTER 8

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