MSc Program
Wood Based Building Design for Sustainable Urban Development

Structural Behaviour and Application of Cylindrical Composite Wooden Tubes

A Master Thesis submitted for the degree of
"Master of Science"

supervised by
Prof. Dr.-Ing. Peer Haller
Institute for Steel and Timber Building
Timber Engineering and Building Constructional Design
Dresden University of Technology

Yu-hsiang Yeh
0628069

Dresden, 05/09/2008

Preface and Acknowledgement

Firstly, I have to thank to Professor Peer Haller, who is the supervisor of the entire research framework. He provides me a robust support, including working space, knowledge and reference resources, to complete the research. Without his immense contribution, I would not have completed the whole research.

Secondly, I appreciate my colleagues in Professor Haller's institute. Andreas Heiduschke, who is an intelligent and funny engineer, gives me immediate instruction and assistance whenever I have problem. Jose Cabrero, who works for the same topic as mine, offers me a deeper perspective on the structural behavior of our research object.

Thirdly, Professor Wolfgang Winter in TU Vienna influences me greatly in research philosophy. He gives accurate and adaptive suggestion in our every presentation and discussion. Professor Bertolini in Turin prepares a series of lectures, excursions and party for us, making our module in Italy attractive. Professor Amino in TU Vienna always inspires me not only in the concept of research but also in other aspects about timber engineering. He is a grateful guide in knowledge exploring. In addition, I have to thank to Katharina as well since she prompts the progress of our program.

Furthermore, all participants of Urban Wood -- Alexandro, Andrea, Arta, Bugra, Bunji, Masa, Miren, Motoko, Tamir -- are the best partners during the whole process. We had fascinating memory in Dresden, Turin and Vienna. Of course we had appealing excursion in Venice and southern Austria as well. I love these cites because we have been there and inscribed reminiscent stories. These are unforgettable memories for me and I will cherish them forever.

Besides the people in Europe, my friends in Taiwan play a significant role in the past one and half year. They did me a great favor physically and mentally. I would like to share the reputation of this study to them.

Finally, my family in Taiwan is the strongest pillar for me. They support me no matter what I request, no matter where I am and no matter when I desire. My achievement would not have been achieved without them. Everything I do is dedicated to my lovely family.

Thanks Sincerely, 27/08/2008, Vienna

Index

Index of Context

Index of Figures

Index of Tables

Index of Charts

Abstract

The purpose of this research is framework to explore the probability and superiority of applying cylindrical composite wooden tubes in practice. The ultimate target is to utilize sustainable material in an efficient and reliable way.

Whole research framework begins from literature review, which provides a universal perspective on the developing history and structural behavior of engineered wood. Subsequent research consists of a series of study and comparison about composite tubes. By comparing, Michaeli's formula is proved to be more conservative and feasible for assessment of the behavior of composite tubes. All comparison, studies and discussion hereinafter depends on the appraisal results from Michaeli's formula.

With the assistance of evaluating formula, the capacity and expected failure modes of a variety of tubes are predictable. This research then plots advisory tables according to the estimated results plus a security factor. Advisory tables offer an avenue for users to adopt tubes in buildings. Furthermore, an application of the assigned tubes is carried out to verify that they are serviceable in an architectural project. It is demonstrated that these tubes are competent for this multi-storey structure.

A comparison about self-weight of various constructions is then executed. This framework testifies that tube-based buildings possess lower self-weight, which elucidates that this construction comprises structural and economical efficiency. In the end, this research conceives a methodology to find out the optimal profile for tubes subjected to certain axial load. This invention precipitates the ultimate target.

Keywords: composite wooden tube, structural behavior, application, design, timber building

Chapter 1 Introduction

1.1 Motives and Purposes

The primary purposes of this research include four parts:

1> to explore the structural behavior of cylindrical composite wooden tubes;
2> to assess the feasibility of tubes in architectural project and organize a facile access to apply them in practical engineering;
3> to prove the efficiency of this engineered wood in buildings compared to other materials;
4> to figure out a methodology to find out the optimal profile for a tube subjected to certain axial load.

Composite material provides the users more and better possibilities in a wide range of industries. In aeronautic engineering, compositing technology helps to compose materials feasible for high heat, high stress and high endurance. In automotive industry, the concept of laminating makes lighter and stiffer elements available. In industrial design, e.g. furniture and tableware manufacturing, composite material offers designers a variety of resources to create products with competent quality and appealing appearance.

The philosophy of composite is quoted in the civil engineering and architecture as well. Reinforced concrete, i.e. concrete with steel consolidation, is the most well-known material in building engineering. Nowadays, experts attempt to blend various materials to acquire an adaptive component for diverse circumstances. For example, glass fiber or carbon fiber is applied in reinforced concrete construction to assure the tensile resistance. With this synthetic fiber, brick walls gain greater ultimate strength in terms of moment.

Wood has become widely applied since the sustainable issues and light-weight construction arose. Due to the intrinsic property of timber, wooden material may consist of defect somewhat. In order to solve these essential imperfections and satisfy the practical desire, engineers adopt diverse materials and techniques to enhance wooden products. Among these improving methods, resin and fiber are the most general means of reinforcement. Fiber, including glass fiber and carbon fiber, may play a role of constraining deformation and thus increase stiffness or strength in certain dimension. Resin not only improves the integration of fibers and reduces the innate flaw in wood, but also promotes robust combination between wood and reinforcing fiber.

Besides the application of various reinforcing materials, advanced manufacturing technologies for requested shape assist greatly in wooden composite products. With modern fabricating techniques, engineers could mould or connect wooden elements to acquire specialized shapes which possess structural and economical efficiency. The so called efficiency refers to less resource consumption, higher material property and better desire feasibility. Considering the concept of shape efficiency, I-shape, rectangular and loop-shaped section are the most common instances.

Cylindrical wooden tube with filament reinforcement emerged recently. This element is composed of re-formed cylindrical wooden tube, glass fiber and the resin which combines the former materials. Since the loop-shaped section contains higher moment inertia, with a given area of cross section, cylindrical tubes can afford higher bending moment. Depending on the filament which can restrain the deformation in certain orientation, the stiffness and ultimate strength may increase significantly in corresponding direction. Thus, the cylindrical composite wooden tubes can be applied for various situations and perform well for different utility. What this thesis deals with is to demonstrate the serviceability of this engineered wood.

1.2 Methodologies and Procedures

In the framework of this research, analytic method is the principle avenue to predict the structural behavior of cylindrical composite wooden tubes. With a global consciousness on the loading capacity and relative structural response of tubes, this research would issue a set of manual tables for users. These manual tables provide advice for designers and engineers to select the competent tubes for specific level of load.

Nowadays, researchers attempt to figure out appropriate evaluating formulae to predict the material property of composite material and estimate the structural behavior of the processed products. These formulae, however, may not function accurately and perfectly for composite wooden tubes because of the essential characteristic of its material. Due to this discrepancy, a comparison between formulae would be carried out. This is to retrieve a relatively conservative formula for timber engineering.

Based on the modern manufacturing technology, the composite wooden tubes are available in ways of different geometries and diversified reinforcements. The profile of composite wooden tubes may diverge extremely for assigned working situations. This research firstly assumes a series of tubes which vary in terms of geometry and filament angle. The assuming plane depends on the general dimension in practical building engineering. Then, the structural behavior, especially the ultimate load and failure mode of each single tube, are available with the appraising formula selected in the former step.

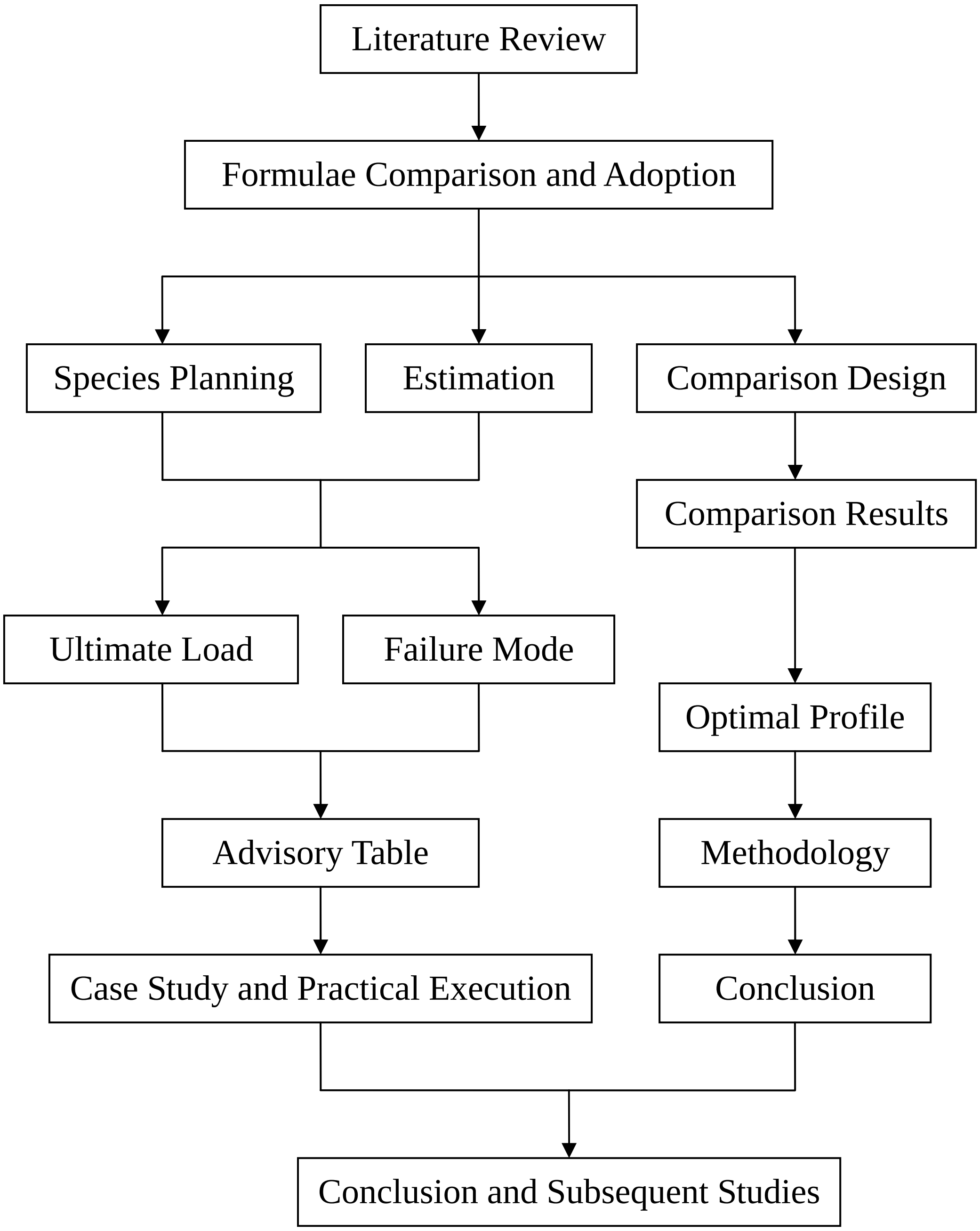
Which tube is most feasible for an assigned load becomes clear with awareness of structural behavior of each tube. This research offers an advisory table for designers and engineers to decide the adoptable tube for desire. Given a certain load, engineers can seek for an appropriate element to satisfy the structural and economical request. The advice emphasizes on structural security and financial consideration simultaneously.

This research will apply the tubes among the assigned candidates in an architectural design project with the assistance of the advisory table. This exercise testifies that the advisory table is an easy and practical manual book for architects or civil engineers.

Furthermore, this research will carry out a comparison to evaluate how efficient the wooden-tube buildings are. This comparison verifies the structural and economical efficiency of tubes construction compared to those composed of traditional sawn wood and other materials. The efficiency here is mainly represented by self-weight of the whole constructions because it refers to less material consumption and less invention requirement.

In the end, this research will figure out a methodology to find out the optimal profile for tubes. This procedure corresponds to the ultimate purpose of researches about engineered wood, which is to consider a sustainable, reliable and adoptable way to utilize natural materials.

1.3 Framework



1.4 Expected Results

This research is intended to discover five questions and find out reliable solutions to these problems:

1> which is the feasible formula to estimate the structural behavior and capacity of cylindrical composite wooden tubes?
2> how these tubes behave and what is the failure mode under axial load?
3> if these tubes serviceable in practical engineering and how can they be applied in architectural design?
4> how efficient and economical are the buildings, which are made of wooden tubes, compared to traditional constructions?
5> how to find out an optimized profile for tubes subject to a given axial load?

The ultimate purpose of this research is to apply the cylindrical composite wooden tubes in architectural design and civil engineering practice. Regarding the structural security and economical demand, this research consists of a series of studies to examine how feasible and beneficial the composite tubes are and how designers can utilize these products. In the other hand, the perspective of the characteristics of composites tubes becomes clear and a facile methodology about using tubes arises.

Since an explicit access to adopt tubes is revealed, designers and engineers have more confidence and stronger fundament to execute a building composed of cylindrical composite wooden tubes. This kind of construction can serve as a sustainable and reliable choice for human environment.

Chapter 2
Structural Behavior of
Cylindrical Composite Wooden Tubes

2.1 Development of Contemporary Wooden Architectures

Wood is a traditional building material and appears world-widely. Since thousands of years ago, it has been adopted for structures, decorations and human tools. With the emergence and application of reinforced concrete and steel, wood became a secondary option for human environment and life due to some essential defects of it and the superiority of other materials like steel and reinforced concrete.

Figure 2.1-1 Wohnüberbauung Hegianwandeweg in Zürich【1】

Nowadays, wood has become a feasible and reliable material in a variety of practical engineering as a result of promotion of technologies and the rise of sustainable philosophy. In building field, wood was generally applied in houses. Wooden construction accounts for a considerable proportion of individual mansions and low-rise housing in some European countries, USA and Canada【2】【3】.

Besides houses, wooden structures are carried out in various sorts of buildings. Industrial constructions may be composed of wooden materials【4】. This adoption comprises an advantage of light-weight, low-cost and short time allocated for project. Wooden office buildings exemplify an application of timber engineering【5】. These examples declare that wooden structures can serve and function well as different building types.

Figure 2.1-2 factory building in Langenthal, Switzerland【4】

Figure 2.1-3 business-center Grenchenstrasse, in Biel, Switzerland【5】

Figure 2.1-4 industrial and office building Grossweid, in Rain, Switzerland【5】

By means of state-of-the-art techniques in timber engineering, not only multi-storey buildings but also free-form constructions composed of wood become possible and applicable. Figure 2.1-5 depicts a 6-storey dwelling in Switzerland whose project period of timber part takes only 3 months【6】.

Figure 2.1-5 6-storey and multi-family housing, Switzerland【6】

Among Tessin Canton, Switzerland, exist buildings comprising large-dimension and distant-span structures built by laminated wood【7】. These projects elucidate that manufacturing technologies make shaped wooden products available and reliable.

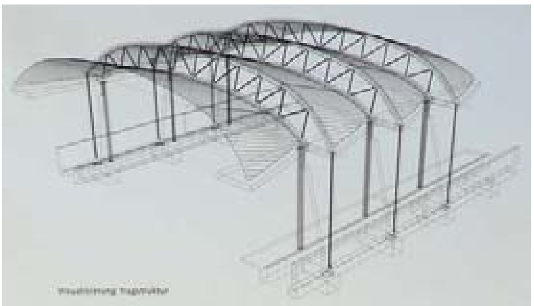


Figure 2.1-6 Substance-workshop FART, Ponte Brolla, Switzerland【7】

Figure 2.1-7 Substance-workshop FART, Ponte Brolla, Switzerland【7】

Figure 2.1-8 is a skywalk bridge which is erected by laminated wood and spans by 29 meters above Muggio valley. This example corroborates as well that the engineered wood can afford not only heavy load but also weathering affect.

Figure 2.1-8 Skywalk in Valle di Muggio【7】

Wooden construction has become a reliable solution in architectural and civil engineering aspects. The evolution from traditional sawn wood to laminate or composite wooden material offers a wider range of possibilities to utilize timber for diverse requirements. Designers and engineers, however, still need more advanced products and further technologies and knowledge to pursue emerging desire and adopt the engineered wood more appropriately.

2.2 Introduction of Composite Wooden Products

In the initial phrase, timber engineering material mainly consists of plywood, particle boards and hard-fiber boards【10】. Figures 2.2-1 to 2.2-3 are samples of the earlier engineered wooden products. Advanced manufacturing techniques and compositing philosophy precipitated the subsequent wood-based products, which include OSB (oriented strand board), LVL (laminated veneer lumbers) and PSL (parallel strand lumber) etc.

Figure 2.2-1

Plywood

Figure 2.2-2

Particle Board

Figure 2.2-3

High Density Fiberboard

Figures 2.2-1 ~ 2.2-3 are instances of early engineered wood, while figures 2.2-4 ~ 2.2-6 reveal the scheme and appearance of advanced wood-based materials.

Figure 2.2-4 OSB

Figure 2.2-5 LVL

Figure 2.2-6 PSL

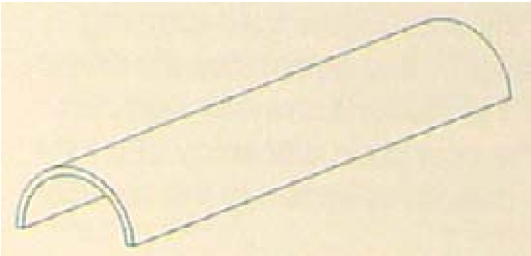
Glulam, which refers to a composition of laminated wood and glue, satisfies the desire for large-dimension timber engineering elements. This building material appears in the structures with distant span and huge cross-section. Figure 2.2-7 and 2.2-8 shows the practical case of glulam construction.

Figure 2.2-7 Glulam for beams
in a junk-addressing field in suburb of Vienna

Figure 2.2-8 Glulam for columns
in Salinen Co., around Salzburg

Nowadays, advanced manufacturing technique makes diversified engineered wooden products available. Engineers can fabricate the laminated wood in specific dimension and profile. This evolution leads to a wide extent of possibilities to produce wooden components for multiple utilities. Since the shape of components can be acquired as designer desires, the products may achieve better the functional, economical and even esthetical concern.

Figure 2.2-9 ~ 2.2-12 demonstrate the achievement of the stat-of-art timber engineering. With assistance of heating techniques and intrinsic properties of wood, timber is considered as a moldable material instead of a brittle one. Compacting technology makes the homogenization of irregular natural material executable. The possibility of molding allows the wood to be exploited precisely for engineering purpose.



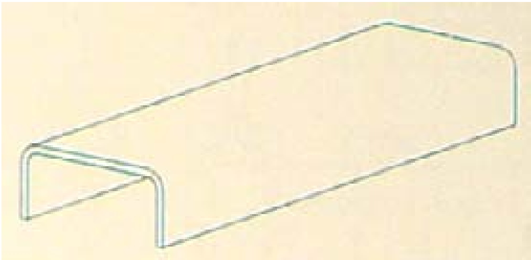
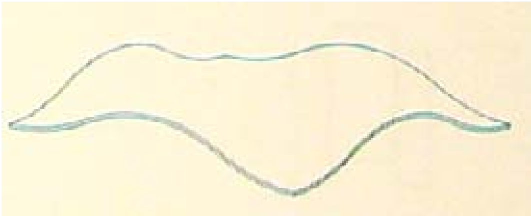


Figure 2.2-9 half cylinder【11】

Figure 2.2-10 narrow rectangular form【11】



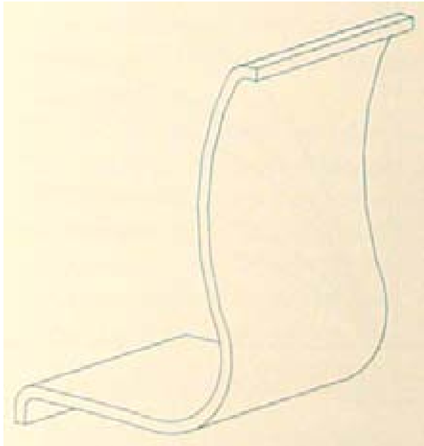


Figure 2.2-11 multiple-curvature shell【11】 Figure 2.2-12 chair shape【1】

Other shaped wooden products, like elements with shaped cross-section, are illustrated in figure 2.2-13 and 2.2-14.

Figure 2.2-13 rectangle cross-section element Figure 2.2-14 I-profile elements

Wooden tubes are cylindrical elements with hollow core and made of laminated wooden plate. Because of the global appearance, wooden tubes possess a ring-like cross-section. In the meanwhile, tubes with square, rectangular or oval cross-section are available as well depending on how the tubes are composed of. These kinds of hollow cross-sections consist of higher moment inertial compared to the solid elements with the same area of cross-section. Thus, the cylindrical components contain higher resistance and shape efficiency while subjected to external loads, especially bending effect【12】.

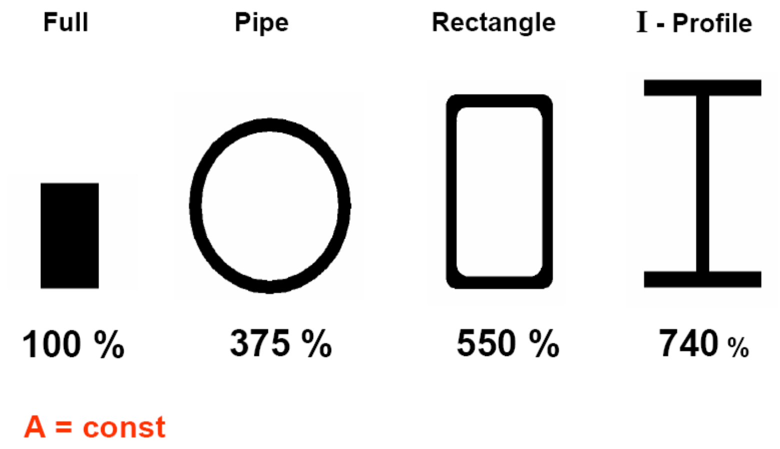


Figure 2.2-15 comparison of moment inertia of various cross-section【12】

Figures 2.2-16 ~ 2.2-18 depict the manufacturing process of cylindrical wooden tubes. Manufacturers fabricate firstly the laminated wooden plate, which would be the wall of tubes. This plate is composed of tinier or remnant elements by means of laminating and adhesive techniques. Manufacturers then soften and reform the laminated plate into curvature profile. In the end, the plate is connected and consolidated into a cylindrical tube.

Figure 2.2-16 tube’s wall

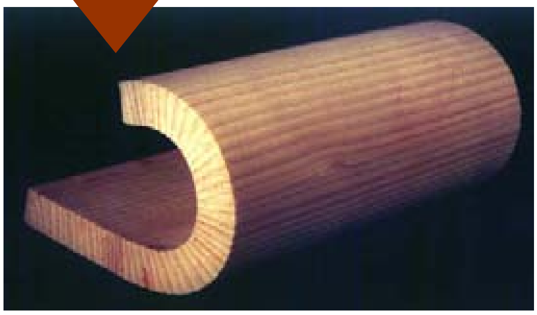


Figure 2.2-17 folding walls

Figure 2.2-18 firming walls into tubes

The forming procedures are illustrated in Figure 2.2-19【12】.

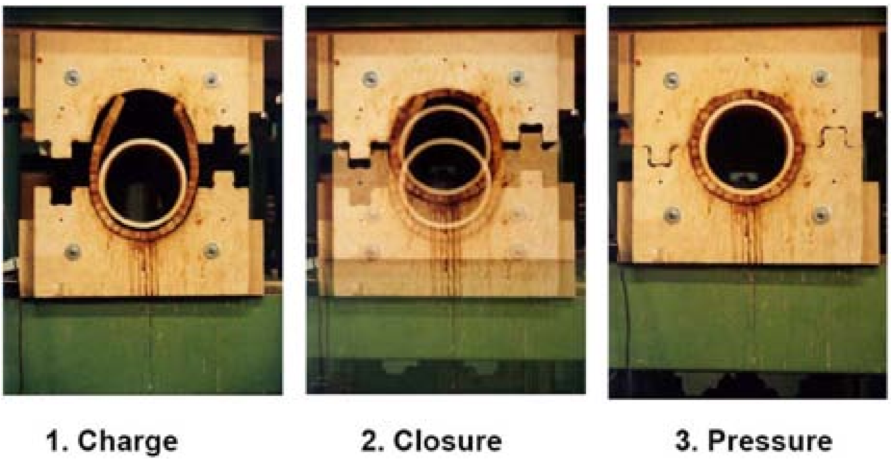


Figure 2.2-19 forming procedures from plate to tube【12】

The cylindrical wooden tube without reinforcement is an engineered timber product containing higher structural efficiency than sawn wood or traditional processed wood. The structural properties of the tube, however, are difficult to predict and then it is hard to appraise the structural capacity and feasibility of the tube.

For this problem, some strengthening process is required to refine the cylindrical wooden tubes for practical engineering.

CFRP and GFRP, which represent carbon fiber reinforced plastic/polymer and glass fiber reinforced plastic/polymer respectively, are filament-based reinforcement used to strengthen wooden products. Adhered on wooden materials with a designed angle to wood's fiber, the fiber reinforced plastic/polymer (mentioned as FRP hereinafter) could provide restriction to wood and restrain wood's deformation. Then the strength of the whole composite is enhanced owing to the suppressing effect.

Figure 2.2-20 a pattern of woven polymer fiber

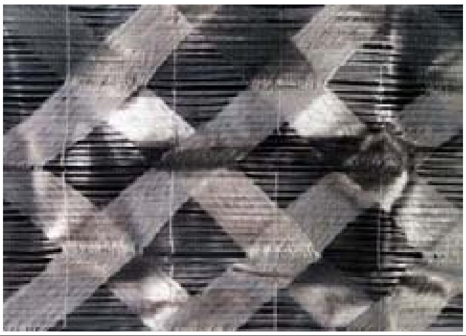


Figure 2.2-21 a way to weave polymer fiber

Engineers wind the FRP on cylindrical wooden tubes and glue them with resin. The adhesive must play a role to provide shear strength and convey the stress between wooden wall and FRP and then the tube can behave as integrity. This reinforced tube is nominated as "cylindrical composite wooden tube" to indicate its ingredients, tectonism and essence. Since the material properties and the sequential structural behavior become predictable, the tube can be applied in practical engineering.

Figure 2.2-22 composite cylindrical wooden tubes【12】

2.3 Material Properties of Composite Wooden Products

As a reinforcement material, FRP plays a role to complement the innate defect of wood. Compared to the tube without fiber reinforcement, the module of elastic (MOE) and module of rupture (MOR) are the most significantly improved factors in cylindrical composite wooden tubes【13】.

Studies about carbon fiber reinforcement rose in 1980's. This material is applied in mechanical engineering, civil engineering and architectures【14】. In building engineering, carbon fiber is widely used for metallic, concrete and wooden constructions to reinforce the components or connections. Xiong et al. investigated the reinforcing ability of FRP for wooden columns by experimental methods. The restraining effect from CFRP mainly exemplifies in three phenomenon【14】【15】:

1) restriction of lateral deformation;
2) area of the loading loop in strain-stress diagram;
3) crack in failure.

Applying CFRP in solid wooden columns can increase the strength and critical load by 10% ~ 20%.

FRP is adopted for strengthening traditional timber structures as well【16】. The connecting philosophy in ancient Chinese timber buildings demonstrates surpassing bending resistance and energy shedding ability. Among these connections, however, it is easy to see the disintegration between motise and tenon and the loose of joints under earthquake attack【17】. Some researchers suggested to adopt FRP to reinforce the connections in ancient Chinese timber buildings【16】【18】.

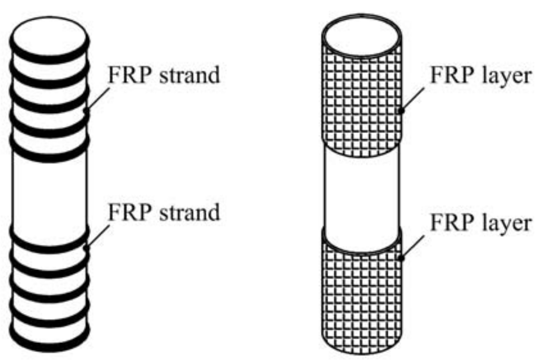


Figure 2.3-1
reinforced column with FRP【16】

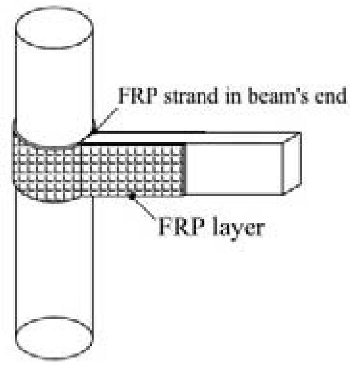


Figure 2.3-2
reinforced connection with FRP【16】

In order to evaluate the reinforcing efficiency of FRP, Xie et al. explored the structural behavior of FRP-reinforced timber structures by means of experiments【17】. The rotational behavior and moment resistance of the connections differ obviously between un-reinforced joint and the FRP-reinforced one. The testing result elucidates that CFRP can make the cyclic behavior more stable and robust and improve the rotational stiffness and strength. In the other hand, CFRP can rehabilitate the deteriorated timber members and joints to the original situation【18】. This results from the restraining function of CFRP.

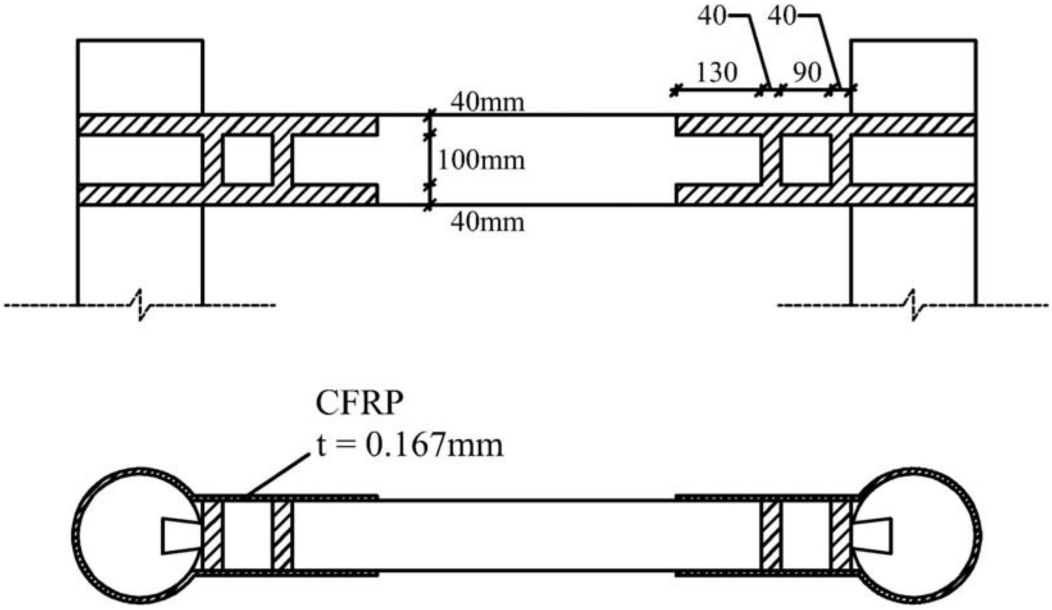


Figure 2.3-3 profile of the reinforcement on connections【17】

2.4 Types of Load and Deformation (Load Imposed on Tubes)

The external forces to which the composite wooden tubes may be subjected mainly include three types, including axial force, bending moment and torsion.

Cylindrical composite tubes subjected to axial loads, with a presumption that only the in-plan effect occurs, the deformation schemes and failure modes consist of three typologies【19】:

1) General/Eular buckling;
2) Local buckling;
3) Compressive failure.

The profiles of three modes are depicted in Figures 2.4-1 ~ 2.4-3

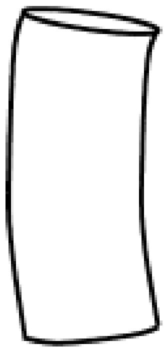


Figure 2.4-1
Eular buckling【19】

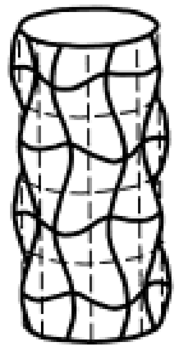


Figure 2.4-2
local buckling【19】

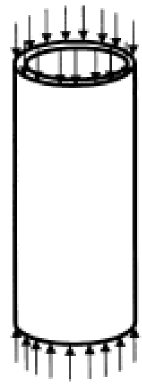
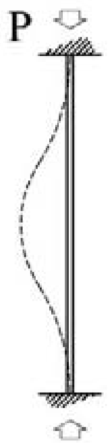


Figure 2.4-3
compression failure【19】

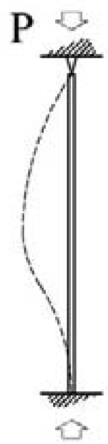
Concerning the Eular buckling in elastic elements, the critical load (Pcr) is desribed as formula 2.4-1, where E is elastic module, I is moment inertia of cross-section and L is the length of an element. Here, K is a factor which varies depending on the boundary condition of the component. The result of K*L refers to efficient length of one member. The value of K, in terms of theoretical derivation, is shown in Figure 2.4-4 ~ 2.4-9.

$$P_{CR} = \frac{\pi^2 E I}{(K * L)^2} \tag{2.4-1}$$



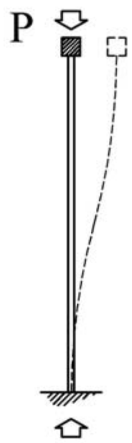
K=0.5

Figure 2.4-4
general buckling type 1



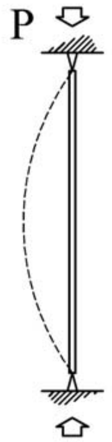
K=0.7

Figure 2.4-5
general buckling type 2



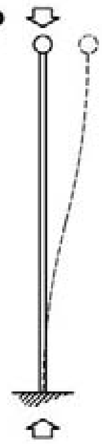
K=1.0

Figure 2.4-6
general buckling type 3



K=1.0

Figure 2.4-7
general buckling type 4



K=2.0

Figure 2.4-8
general buckling type 5

K=2.0

Figure 2.4-9
general buckling type 6

The boundary conditions drawn in figures 2.4-4 ~ 2.4-9 include four types. The characteristics of each end is illustrated and instructed below.

fixed end	movement fixed rotation allowed	movement allowed rotation fixed	movement allowed rotation allowed

Figure 2.4-10 boundary conditions of ends of the element

As Michaeli further illustrated, the local buckling may occur in different ways【20】. In addition to the chessboard-like profile, the ring-like scheme is another prototype of local buckling. In the chessboard local buckling, the longitudinal fibers of the tube deform sinuously or cosinuously. This phenomenon results in crisscrossing allocation of the peak and trough of the wall as drawn in figure 2.4-11. In case of ring-like buckling, the longitudinal fibers deform sinuously and cosinuously simultaneously. Thus the fibers deform in the same curve and the cross-section remains the ring-like profile of different diameter. The ultimate scheme of ring-like local buckling is delineated as figure 2.4-12.

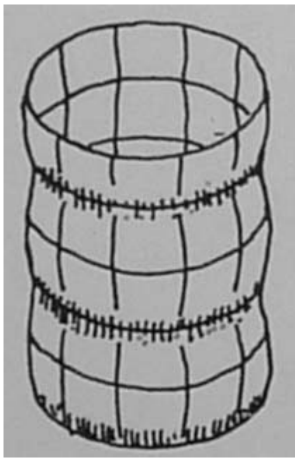


Figure 2.4-11chessboard local buckling【20】 Figure 2.4-12 ring local buckling【20】

Structural response of cylindrical composite components subjected to bending effect caused by lateral loads is important as far as the structural security is concerned. In case of cantilever elements, general beams and eccentrically loaded columns, the lateral loads impose bending moment and shear forces in the members【21】. The structural integrity of such members becomes an interesting object for researchers.

Roberto Lopez-Anido et al. conceived a series of testing to quantify how much the FRP could retrofit the bending resistance【21】. Using FRP reinforcement surrounding the wooden piles can sufficiently enhance the bending capacity. Among the pre-damaged piles, which are damaged by 60% in cross-section, the FRP-reinforced specimens possess 3 times ultimate load of the original one. This result elucidates that FRP can not only recover the bending capacity of a damaged element but also exceed the performance of intact one by 3 times.

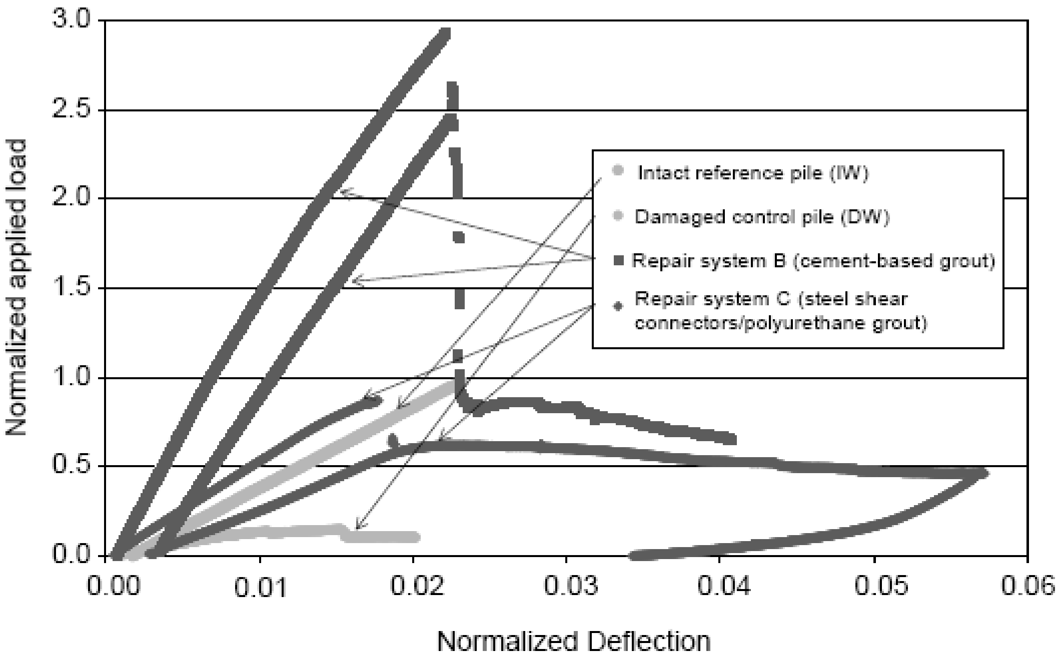


Figure 2.4-13 Normalized load-deflection diagram of various wooden piles【21】

2.5 Evaluating Formulae

Researchers figured out a series of formulae in order to predict the structural capacity and behavior of tubes subjected to axial load.

Weaver attempted to correlate the ultimate stress of the tube with its shape efficiency【19】. The shape efficiency is derived from the ration of the critical load of a shaped element to that of a solid circular section with the same length, area and material. This value reveals how structurally efficient the shaped element is compare to the solid one. Then, this shape efficiency is reduced and transformed into the ratio of the radius of a tube to the thickness of its wall. In Weaver's framework, Φ is adopted to represent shape efficiency and it simply refers to the ratio of radius to thickness.

$$\phi = \frac{r}{t} \tag{2.5-1}$$

Here, shape efficiency, Φ, is dimensionless and depends only on the shape. Solid equiaxed sections, e.g. circles, squares, hexagons and octagons, consist of values close to 1. However, if the profile of section is altered, I-shaped, corrugated or hollow, the results alter. A thin-walled tube or a slender I-shaped element may possess a value of Φ of 50 or more. A shape efficiency of 50 means that the section is more resistant to elastic buckling by 50 times a solid element.

Weaver dealt with the cylindrical columns subjected to compressive axial loads. If sufficiently long and thin, a tube firstly fails by Eular, e.g. elastic or general, buckling. The critical load soars with the increase of the diameter of tubes. Since the area should remain constant for comparison, the thickness correspondingly decreases while the increase. In the meanwhile, the Φ value is getting higher.

The load-carrying capacity cannot increase infinitely. When the Φ value achieves a certain level, the dominant factor for critical load veers. The ultimate load of a cylindrical tube is dominated by local buckling or material failure. Thus, the three competing failure mode include: general/elastic/Eular buckling, local buckling and material failure. The general and local buckles are influenced by the modulus of material and the shape of sections. Material failure is influenced by the compressive material strength and area of cross-section but not by its shape.

If a cylindrical element is long and thin enough, the general buckling occurs at the critical load of F in equation 2.5-2. Here, I is moment inertia and L is the length of a tube.

$$F = \frac{\pi^2 \cdot k_1 \cdot E_{iso} \cdot I}{L^2} \tag{2.5-2}$$

In equation 2.5-2, E_{iso} is the quasi-isotropic elastic modulus of a particular composite system. For example, the E_{iso} of a cylindrical composite wooden tube with filament is derived from wooden wall and FRP layer. Coefficient k_1 is derived from the effect of lay-up. The value of k_1 is largest while all fibers are parallel to the orientation of compression and smallest when they are perpendicular to the load.

By dividing and substituting the equation 2.5-2 by A^2, an expression for the value of the stress σ_1 rises as shown in equation 2.5-3【19】. In the end, the ultimate axial load of general buckling can be acquired by multiplying stress σ_1 by the area A of cross-section.

$$\sigma_1 = \sqrt{\frac{\pi}{4} \cdot k_1 \cdot E_{iso} \cdot \phi \cdot \frac{F}{r^2}} \tag{2.5-3}$$

The second failure mode, local buckling, occurs in case of thin-walled tubes. Once again, the Φ value, the ratio of radius to thickness, indicates how thin a tube is. Tubes buckle when the axial stress exceeds the value of σ_2 in equation 2.5-4【2.5-1】.

$$\sigma_2 = 0.6 \cdot \alpha \cdot E \cdot \frac{t}{r} \tag{2.5-4}$$

Equation 2.5-4 consists of an empirical knockdown factor, α. Young took this factor equal to 0.5. The predicted result, however, becomes not conservative while the r/t ratios are large. This problem results from the interaction of different buckling modes. NASA suggested an adoption of an empirical formula which recognizes a knockdown factor increasing with r/t ratios【25】. Allen and Bulson recommended a modification of equation 2.5-4 with adjusted α【26】. The choice of α influences the ultimate stress

Dow and Rosen described the local buckling phenomenon of cylindrical composite shells【27】. The ultimate stress of local buckling was derived from an equation modified from equation 2.5-4 and appeared as equation 2.5-5.

$$\sigma_2 = 0.6 \cdot \alpha \cdot k_2 \cdot E_{iso} \cdot \frac{t}{r} \tag{2.5-5}$$

In equation 2.5-5, k_2 is a non-dimensional anisotropy factor which alters approximately between 0.4 to 1.0 for polymeric composites.

$$k_2 = \sqrt{\frac{(1-\gamma^2_{iso}) \cdot 2G_{xy} \cdot (1+\sqrt{\gamma_{xy} \cdot \gamma_{yx}})}{E^2_{iso} \cdot \sqrt{E_x \cdot E_y} \cdot (1-\gamma_{xy} \cdot \gamma_{yx})}} \quad \text{or} \quad \sqrt{\frac{(1-\gamma^2_{iso}) \cdot E_x \cdot E_y}{E^2_{iso} \cdot (1-\gamma_{xy} \cdot \gamma_{yx})}} \tag{2.5-6}$$

Replacing the r/t ratio by Φ comes out a new expression for σ_2 shown in equation 2.5-7. This formula is valid for balanced and symmetric laminates.

$$\sigma_2 = 0.6 \cdot \alpha \cdot k_2 \cdot \frac{E_{iso}}{\phi} \tag{2.5-7}$$

The third failure mode is general compressive material failure. This phenomenon occurs when the axial stress exceeds the value of σ_3 in equation 2.5-8, where coefficient k_3 is derived from the effect of lay-up and σ_{iso} is superposition of the composites.

$$\sigma_3 = k_3 \cdot \sigma_{iso} \tag{2.5-8}$$

In the meanwhile, Michaeli figured out a set of formulae to evaluate the structural capacity of cylindrical composite shell subjected to axial load. These formulae are mainly conceived for general and local buckling【20】.

As far as general buckling is concerned, the element buckles when the axial load exceeds the critical level F_b shown in equation 2.5-9:

$$F_b = \frac{\pi^2 E I}{L^2} \qquad (2.5\text{-}9)$$

In equation 2.5-9, E is quasi-isotropic elastic modulus of the entire lay-up as used in equation 2.5-2, I is moment inertia of cross-section and L is the effective length of the tube.

Michaeli modifies equation 2.5-9 for practical application. Since the cross-section is not totally dedicated to affording the load, a reducing factor is necessary for various profiles of cross-sections. In the other hand, when an element buckles, shear may occur, result in a coupling effect and influence the appraisal result of ultimate load. Thus, a modified expression for general buckling is proposed for accurate prediction.

$$F_{bs} = \frac{F_b}{1 + \frac{k}{A \cdot G_{xy}} F_b} \qquad (2.5\text{-}10)$$

In equation 2.5-10, k is reducing factor depending on profiles of section, A is the area of cross-section and G_{xy} is the shear modulus of the entire lay-up. F_b appearing in numerator and denominator is theoretical critical load obtained from equation 2.5-9.

Michaeli adopted two types of formulae for local buckling【20】. These two formulae correspond different prototypes of local buckling which are ring-like and chessboard scheme.

$$F_{ring} = \frac{2\pi}{\sqrt{3}} \cdot t^2 \cdot \sqrt{\frac{E_x \cdot E_y}{1 - \gamma_{xy} \cdot \gamma_{yx}}} \qquad (2.5\text{-}11)$$

$$F_{chess} = \frac{2\pi}{\sqrt{3}} \cdot t^2 \cdot \sqrt{\frac{2 \cdot G_{xy} \cdot \sqrt{E_x \cdot E_y}}{1 - \sqrt{\gamma_{xy} \cdot \gamma_{yx}}}} \qquad (2.5\text{-}12)$$

F_{ring} shown in equation 2.5-11 is critical axial load for ring-like local buckling. When the load exceeds F_{chess} in equation 2.5-12, the shell buckles in ways of chessboard pattern. Here, t is the thickness of the wall and G_{xy} is the shear modulus of it. E_x and E_y are elastic modulus of the wall in x and y orientation and γ_{xy} and γ_{yx} are Poison Ratio of the composite lay-up.

Chapter 3 Object and Comparison Design

3.1 Introduction of Design

This research comprises 5 sections of studies about applying tubes in architectures:
1> comparing and adopting the feasible formula
2> setting a group of tubes for application and evaluating their capacity
3> proving the serviceability of tubes and figuring out a simply advisory table
4> comparing the self-weight of constructions made of various materials
5> searching for the optimal profile of a tube for certain load

The framework and design of each section will be described in this chapter while the results and conclusions will be plotted later in the next one.

Chapter 3.2 is the first section listed above. It is a comparison of two systems of formulae which are conceived by Weaver and Michael respectively. The more conservative one will be adopted in the hereinafter studies. Chapter 3.3 includes a global instruction about section 2 and 3, which contain the methodologies and purposes of the application of tubes. Chapter 3.4 explains how to compare the self-weight of constructions made of steel, RC, sawn wood and wooden tubes. This paragraph reveals the fundamentals for comparing. Chapter 3.5 is the 5th section of the whole research and intended to explicate how to approach an optimal scheme of a tube for an assigned load.

3.2 Feasible Evaluating Formulae

A simple study about reliability of evaluating results from formula is carried out in order to find out the feasible estimating formula. Two systems of formulae are applied for a variety of tubes to compare. These tubes vary geometrically in terms of length, shape efficiency Φ and cross-section area. Except for these variables, other conditions like material properties are equal. The three variables are listed in table 3.2-1

【Table 3.2-1 geometrical factors of tubes】

variable	meaning	instruction
L	length of a tube	
Φ	r/t	r: radius, t: thickness
A	area of cross-section	only the wooden wall
M	mass of a tube	

The range of each variable should correspond to the practical situation in general buildings. Thus the length of the explored tubes distributes between 2.6 meters to 7.0 meters. These are the most common length of one storey in general buildings such as houses, low-rise housing and office architectures.

Higher Φ value refers to higher shape efficiency. Theoretically, a section with high Φ value may be preferential for efficient consideration. In building engineering, however, it is seldom to use a tube with extremely high Φ value because a tube with such thin wall is unreliable. Therefore, the Φ values in this research are set between 6.25 and 42.25.

The range of variables is shown in table 3.2-2. The reasonable interval is applied to reduce the amount of analysis.

【Table 3.2-2 range and interval of variables】

	range and the interval									
L	2.60	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00
Φ	6.25	9.00	12.25	16.00	20.25	25.00	30.25	36.00	42.25	
A	157	100	120	180	220	260	300	340	380	420
unit of length L: meter unit of cross-section area A: cm^2										

In the comparison, only one variable alters at one time and others keep constant. For example, when the length varies from 2.6 to 7.0 meters, the shape efficiency Φ and cross-section area A remain the same. When the cross-section area alters, the shape efficiency Φ and length of a tube L remain constant. The situation of each variable in comparison is shown below.

1. variable: L
   with fixed Φ and A => mass is various
2. variable: Φ
   with fixed A and L => mass is constant
3. variable: A
   with fixed Φ and L => mass is various

The material properties are listed in table 3.2-3. These data reflect a lay-up which consists of a wooden wall and carbon fiber polymer.

【Table 3.2-3 material properties of wood and carbon fiber】

parameters	assumed value of wood	assumed value of carbon fiber
E_x	16,800 MPa	30,000 MPa
E_y	1,000 MPa	3,000 MPa
G_{xy}	500 MPa	1,000 MPa
ν_{xy}	0.013	0.003
ν_{yx}	0.4	0.3
σ_c	55 MPa	55 MPa
geometric data	depending on design	depending on design

3.3 Adopted Geometries of Tubes

The representative geometrical parameters depicting a tube comprise four items:

1> diameter of cross-sections
2> thickness of the wall
3> angle and layers of filament
4> length of whole tube

The dimension of the studied tube is supposed to correspond with the most common dimension in practical buildings. Therefore, the values of these four parameters have to be set in a certain extent.

This research adopts the inner diameter of a tube to refer to the diameter of it. The values of inner diameter are assumed from 10 cm to 54 cm. It would be the universal dimension of elements in general houses, collective housing and office buildings. Figure 3.3-1 delineates the definition of diameter in this framework.

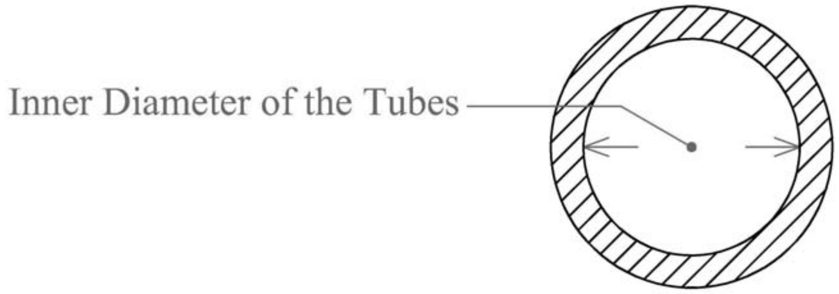


Figure 3.3-1 parameter 1 -- inner diameter

With consideration both on common dimension of elements and benefit of shape efficiency, the thickness of wooden wall are designated as 2 cm and 3 cm. Figure 3.3-2 illustrates the connotation of thickness. The “thickness” here represents only how thick the wooden plate is without the lay-up of filament reinforcement.

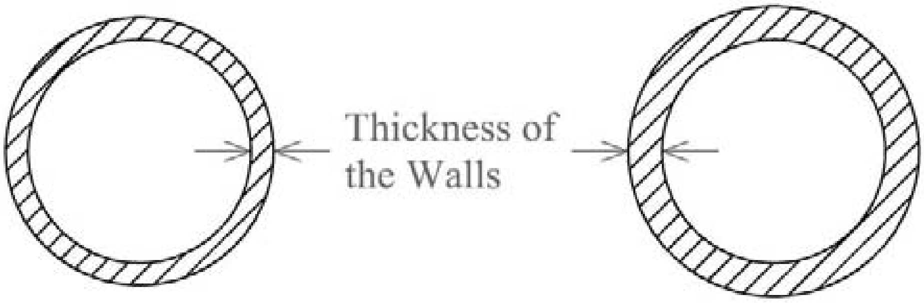


Figure 3.3-2 parameter 2 -- thickness of wooden wall

FRP reinforcement can be applied on the tube in different ways and the primary geometrical discrepancy exemplifies in the angle between carbon fiber and wooden fiber. The wood's fiber is generally parallel to the longitudinal orientation of tubes in order to ensure the material efficiency. Angles of carbon fiber and wooden fiber are therefore equal to the angles between carbon fiber and the tube.

When carbon fiber is perpendicular to the wooden fiber, the angle is defined as 0. Thus, the angle is defined as 90 degree when carbon fiber is parallel to wooden fiber. In the comparison design, angles of carbon fiber are set as integers like 0°, 10°, 15°, 30°, 45°, 60° and 90° etc. The scheme of filament reinforcement is depicted in figure 3.3-3.

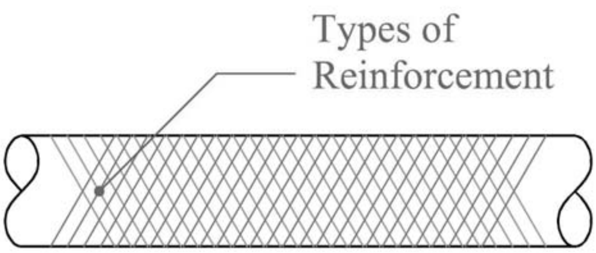


Figure 3.3-3 parameter 3 -- angle of fiber reinforcement

As shown and explained in chapter 3.2, the length of tube varies between 2.5 meters to 7.0 meters and the interval is equal to 0.25 meter.

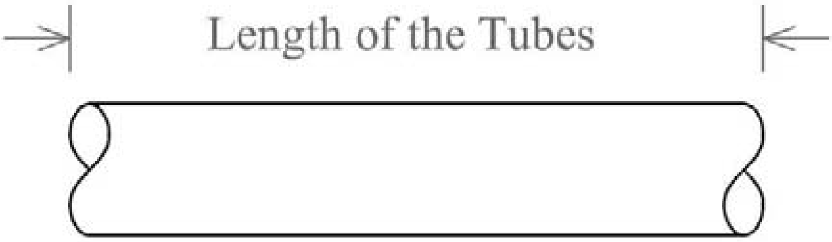


Figure 3.3-4 parameter 4 -- length of a tube

In the end, each parameter and its range and interval are shown in table 3.3-1. Setting this extent and interval of dimension is to evaluate the capacity and efficiency of composite wooden tubes compared to other materials like steel, reinforced concrete and sawn wood. This arrangement can exam if tubes functions when it is ordinary as common scale.

【Table 3.3-1 design profiles of controlling parameters】

	range	interval
inner diameter	10 ~ 54 cm	4 cm
thickness of the wall	2cm & 3cm	1 cm
angle of filament	0° ~ 90°	shown hereinafter
length of a tube	2.5 m ~ 7.0 m	0.25 m

Figure 3.3-5 ~ 3.3-12 delineate the scheme of fiber reinforcement on tubes. In this framework, the amount of filament layers is two and the angles are designated as geometrically representative value like 10°, 30°, 45° and 60° etc.

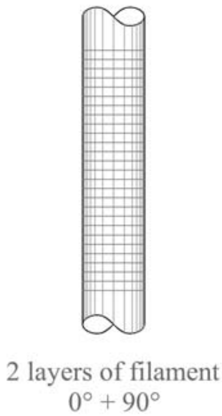


Figure 3.3-5

scheme 1 of fiber layers

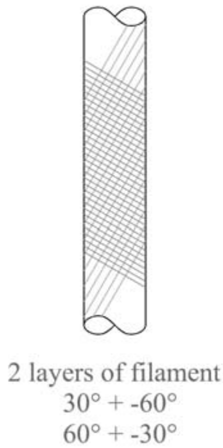


Figure 3.3-6

scheme 2 of fiber layers

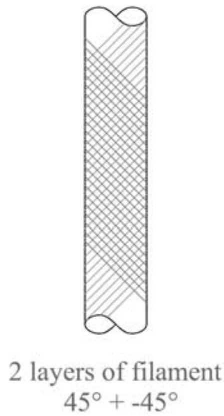


Figure 3.3-7

scheme 3 of fiber layers

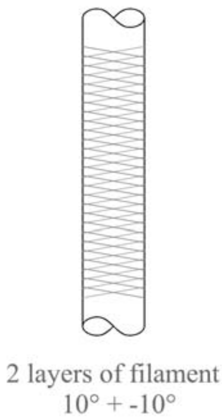


Figure 3.3-8

scheme 4 of fiber layers

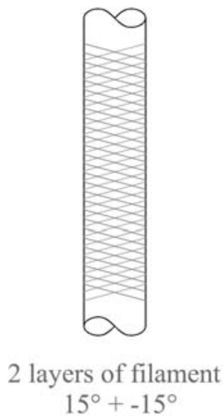


Figure 3.3-9

scheme 5 of fiber layers

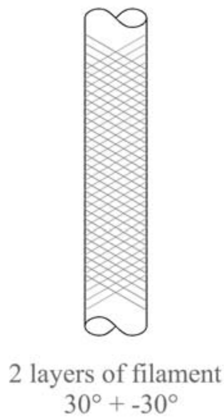


Figure 3.3-10

scheme 6 of fiber layers

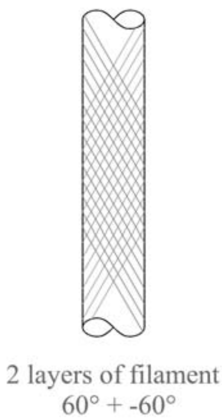


Figure 3.3-11

scheme 7 of fiber layers

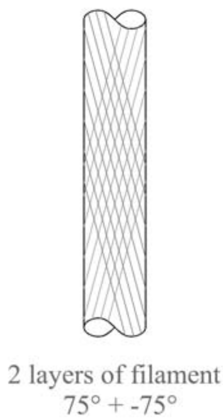


Figure 3.3-12

scheme 8 of fiber layers

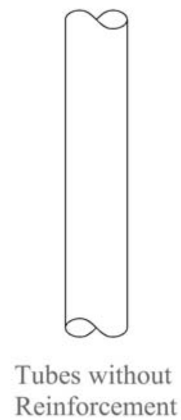


Figure 3.3-13

tube without fiber

The material properties of wood and fiber in this assessment framework are plotted in table 3.3-2. Then, the E_{xiso}, E_{yiso} and G_{iso} of the entire composite are derived from the given material properties depending on isotropic laminated material concept. These values are required by means of matrices and calculating process is executed by MathCAD program.

【Table 3.3-2 material properties of wood and fiber】

parameters	assumed value of wood	assumed value of carbon fiber
E_x	16,800 MPa	26,100 MPa
E_y	1,344 MPa	10,280 MPa
G_{xy}	1,200 MPa	4,140 MPa
ν_{xy}	0.041	0.09
ν_{yx}	0.4	0.3
σ_c	55 MPa	55 MPa
geometric data	depending on design	depending on design

Ultimate loads of tubes in the study frame are listed in chapter 4.3. In the meanwhile, a case study in chapter 4.3 would prove that the composite tubes are reliable and feasible for multi-storey timber building. This case study depends on an architectural project in Vienna, which is 5~6-storey building made of wood for department of architecture. Sequentially, a study about the capability of tubes would elaborate for which building the tube-based construction is affordable.

Finally, an advisory table which is conceived depending on the appraising results will be plotted. This table provides a simplified method for designers or engineers to apply composite tubes in buildings.

3.4 Comparison for Self-weight

Self-weight of a building may represent the seismic resistance of it. Lighter buildings suffer from low horizontal force caused by earth motion. Wooden buildings consist of lower self-weight compared to constructions built by steel and reinforced concrete. Therefore, wooden houses generally afford lower horizontal force than other constructions do.

Advanced wood-based buildings, e.g. a house built by composite wooden tubes or other engineered woods, may possess less self-weight compared to traditional sawn wood. With these characteristics, buildings composed of composite wooden tubes may need to resist lower lateral force from seismic effect than traditional wooden buildings have to take. In the other hand, constructions of composite tubes consume less material than traditional wood-based one.

Buildings built by composite wooden tubes manifest structural efficiency and economical superiority compared to those of traditional wooden material. The accurate advantages, however, is not explicit and need to be quantified. This research thus figures out a simple model for each constructional material to compare the self-weight of buildings built with these materials. Involved material within the comparison framework includes four candidates:

1> steel
2> reinforced concrete
3> sawn wood (traditional wood-based structures)
4> composite wooden tubes

To make a comparison, this research designates a model which is shown in figure 3.4-1. As delineated below, this is a post-and-beam construction, containing only columns and beams.

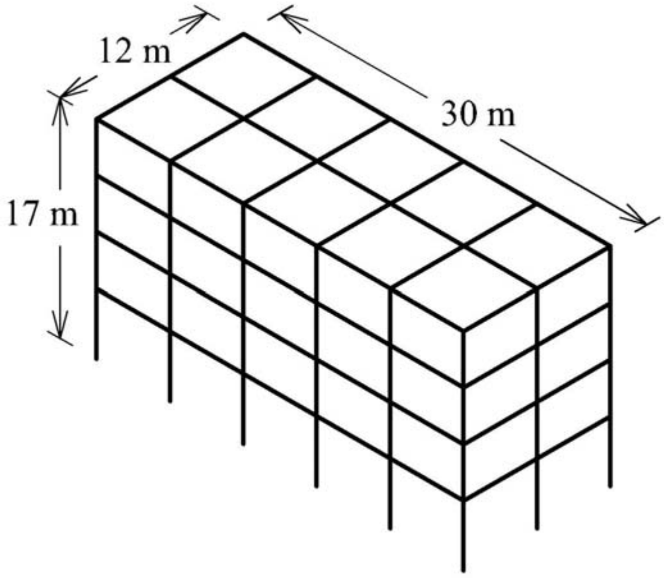


Figure 3.4-1 building model for comparison

This model refers to common houses or office buildings. In order to compare the self-weight in a fair, reasonable and general foundation, some conditions are cited for this model:

1> 4-storey
2> no walls or any kind of vertical panel is applied in this model
3> all joints are rigid, i.e. moment resistant connections
4> all members, including columns and beams, are elastic elements

Because the profiles of walls and openings may vary extremely depending on the design, the “self-weight” in this research does not include these vertical panels. Thus, this model can be considered as a complex of a series of frames which are combined by means of elastic elements and rigid connections. Figure 3.4-2 illustrates the scheme and dimension of a frame. As instructed in former paragraph, this frame consists of only columns, beams and rigid joints.

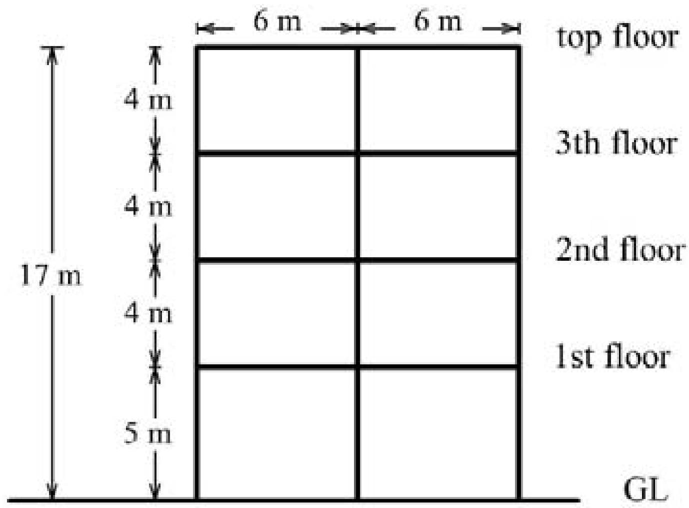


Figure 3.4-2 one frame in the model

A reasonable comparison, however, has to take the dead load of horizontal deck and live load from the floor into account. Therefore, the loading scheme of one frame includes not only the self-weight of frame but also the vertical load from floor. Figure 3.4-3 demonstrates all loads in one frame.

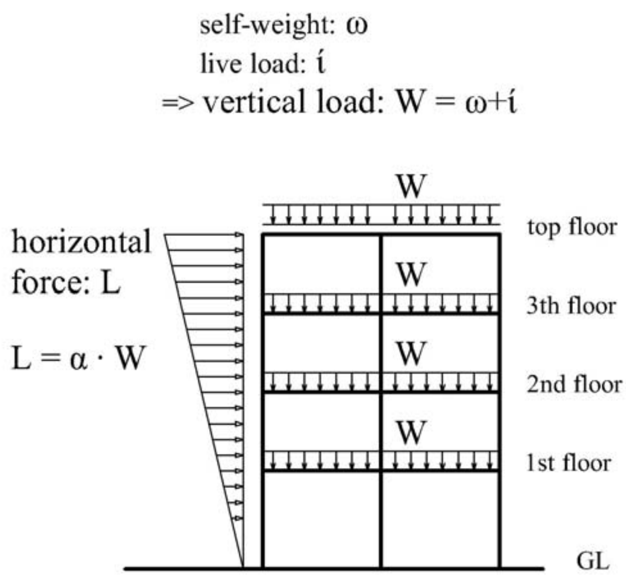


Figure 3.4-3 profile of a frame and the scheme of all loads

Vertical load contains two origins:

1> self-weight of floor and components

2> live load which is determined by the function of the building

Basic prerequisites of vertical loads are listed in table 3.4-1. Materials applied in this comparison framework are general options for normal buildings. Properties of each material are plotted in table 3.4-2.

【Table 3.4-1 prerequisite data for vertical load】

	material of floors	thickness of floor	dead load from floor*1	live load in floor	W*2
steel	concrete	30cm	7.65 kN/m^2	5 kN/m^2	12.65 kN/m^2
RC	concrete	30cm	7.65 kN/m^2	5 kN/m^2	12.65 kN/m^2
sawn wood	wood	30cm	1.50 kN/m^2	5 kN/m^2	6.50 kN/m^2
wooden tubes	wood	30cm	1.50 kN/m^2	5 kN/m^2	6.50 kN/m^2

Note1: Density of concrete and wood influences the dead load from floor. The values of the density of each material refer to table 3.4-2.

Note2: W is shown in figure 3.4-3, which includes dead load and live load of floor.

【Table 3.4-2 material properties of each source】

	density	elastic module	shear module
steel	78.0 kN/m^3	210,000 MPa	81,000 MPa
RC	25.5 kN/m^3	34,000 MPa	15,000 MPa
sawn wood	5.0 kN/m^3	11,000* MPa	550 MPa
wooden tubes	5.0 kN/m^3	16,800* MPa	1,365 MPa

Note: Elastic and shear module of sawn wood and wooden tube should be equal. The tubes, however, possess higher material properties because the wood has been reinforced by FRP. Material properties thus become higher than traditional wood.

Lateral force L in figure 3.4-3 is caused by ground motion. The volume of lateral force depends on a variety of parameters such as ground acceleration, vibration period of structures, function of buildings, material of constructions and self-weight of architectures. According to Taiwanese building design norm, minimum horizontal force caused by earthquake and afforded by a building is derived from the formula as equation 3.4-1.

$$V = \frac{S_{aD} \cdot I}{1.4 \cdot \alpha_y \cdot F_u} W \qquad (3.4\text{-}1)$$

In equation 3.4-1, V is the minimum horizontal force which one building should take. It is equal to L in figure 3.4-3. S_{aD} is a factor varying with ground acceleration of building sites. I value is derived from the functions of buildings. α_y is an amplifying multiple for yielding point of earthquake force, which depends on the material and design methodology. F_u is a reducing factor of earthquake force, which varies in accordance with structural system, material and tenacious capacity. W in this formula is self-weight of the buildings.

Since the evaluating procedure is complicated and needs plenty data which are particularly for certain location, this research would simply the appraising process for ordinary comparison. The relation between vertical load and horizontal force is set 0.3282 in this comparing framework.

After imposed entire vertical and horizontal force, the building model will deform somewhat in both local and global ways. Deforming scheme of the model is demonstrated in figure 3.4-4. Local deformation in each member and global displacement of whole building occur simultaneously.

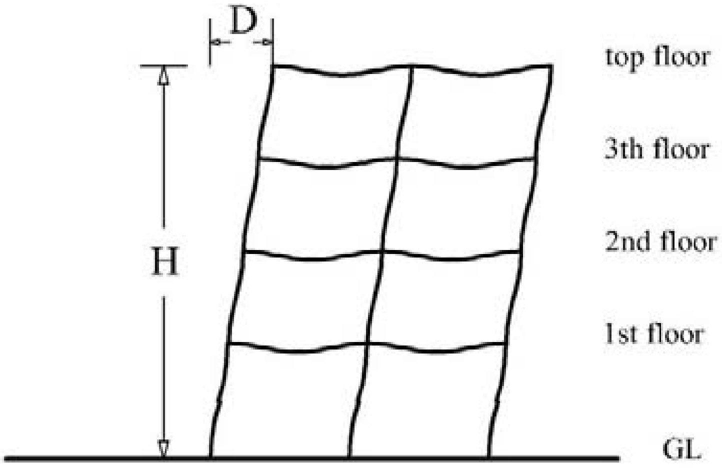


Figure 3.4-4　deformation scheme of the model after loaded

Calculating work is carried out by means of RSTAB, which is a structural analysis program.　The calculated results contain the necessary data of stain and stress, such as normal force, bending moment and displacement of nodal points and elements.

H shown in figure 3.4-4 is the height of the designated building model, which is equal to 17 meters.　D in the figure is displacement of the building caused by all imposed loads, which happens mainly horizontally.　The ratio of D/H is defined as the stiffness of this building when it is subject to loads.　For comparison, D/H ratios of the four constructional materials are set to be approximately 1/200 as possible as it could be.　By doing so, this research assigns each construction the same rigidity.

To satisfy this stiff criterion, each building model needs appropriate dimension of elements to qualify it.　After the dimension of all components of each construction, it is possible to assess the self-weight of these building models in a reasonable fundamental.

3.5 Optimal Profiles of Tubes under Certain Loads

This section inherits the result of previous one. With assistance of RSTAB, the necessary deformation data are available. Then, this research selects the tube affording the highest axial load and attempts to find out the optimal profile for this loading condition.

Definition about "optimal" profile needs to be determined firstly. In this framework, the meaning of optimized profile of a tube subject to certain design load is described below as:

A tube whose ultimate capacities of three failure modes are above and close to the design load

Under this rule, this research conceives a methodology which would satisfy the requirement above to find out the optimal scheme of tubes.

A cylindrical composite wooden tube comprises three failure modes and corresponding estimating formulae. Within each failure mode exists a dominant, or at least relatively dominant, factor. If these dominant factors are fixed, the ultimate for that failure mode would be known. Therefore, adjusting these significant factors can alter the profile of the tube and make it more optimal.

First mode is compressive failure, which exemplifies in crack, crumble or split of wood. The formula used for predicting ultimate stress of this mode is demonstrated as equation 3.5-1.

$$\sigma = k \cdot \sigma_{iso} \qquad (3.5\text{-}1)$$

$$F_{compression} = \sigma * A \qquad (3.5\text{-}1)$$

By multiplying the stress σ by A, which is area of cross-section, the ultimate load $F_{compression}$ arises. With a given material and lay-up of composite, the ultimate stress σ is obtained. $F_{compresson}$ thus would vary by adjusting the value of A.

For the second failure mode, i.e. general buckling or Eular buckling, the estimating formula is shown in equation 3.5-2. Within this theoretical framework and with a given material properties and geometry, moment inertia I thus becomes the dominant factor for general buckling.

$$F_b = \frac{\pi^2 E I}{L^2} \qquad (3.5\text{-}2)$$

Subsequently, the formula would be modified into an expression demonstrated as equation 3.5-3 with consideration of shear effect. Generally, F_{bs} represents the ultimate load of Eular buckling.

$$F_{bs} = \frac{F_b}{1 + \frac{k}{A \cdot G_{xy}} F_b} \qquad (3.5\text{-}3)$$

Although equation 3.5-3 consists of several variables like cross-section area, shape factor and shear module, F_b derived from equation 3.5-2 is the most significant items in equation 3.5-3. Therefore, moment inertia remains relatively dominant compared to other factors. It is thus possible to infer that ultimate load for general buckling differs mainly depending on I value and adjusting I value make the F_{bs} approach the design load.

Local buckling is the third failure mode for cylindrical composite wooden tubes imposed axial load. This failure scheme consists of two types and both of them have corresponding appraisal formula. Formula for ring-like local buckling is shown in equation 3.5-4 while the formula for chessboard local buckling is described as equation 3.5-4.

$$F_{ring} = \frac{2\pi}{\sqrt{3}} \cdot t^2 \cdot \sqrt{\frac{E_x \cdot E_y}{1 - \gamma_{xy} \cdot \gamma_{yx}}} \qquad (3.5\text{-}4)$$

$$F_{chess} = \frac{2\pi}{\sqrt{3}} \cdot t^2 \cdot \sqrt{\frac{2 \cdot G_{xy} \cdot \sqrt{E_x \cdot E_y}}{1 - \sqrt{\gamma_{xy} \cdot \gamma_{yx}}}} \qquad (3.5\text{-}5)$$

Inspecting these formulae, it indicates that several parameters may influence the ultimate load of local buckling. With given material properties and geometrical data except for thickness, however, every parameter becomes determined when the thickness is decided. Thus, the value of thickness, i.e. t in these two equations, may govern the evaluating results.

The approaching methodology, related conclusion and the restriction would be clarified in chapter 4.5.

Chapter 4
Analysis Results and Discussion

4.1 Comparison of Two Systems of Formulae

The compared formulae in this research are demonstrated in table 4.1-1.

【Table 4.1-1 evaluating formulae conceived by Weaver and Michaeli】

	Weaver	Michaeli
compressive failure	$\sigma = k \cdot \sigma_{iso}$	$\sigma = k \cdot \sigma_{iso}$
general buckling	$\sigma_1 = \sqrt{\frac{\pi}{4} \cdot k_1 \cdot E_{iso} \cdot \phi \cdot \frac{F}{r^2}}$	$F_b = \frac{\pi^2 E I}{L^2}$
reduced general buckling		$F_{bs} = \frac{F_b}{1 + \frac{k}{A \cdot G_{xy}} F_b}$
ring-like local buckling	$\sigma_2 = 0.6 \cdot \alpha \cdot k_2 \cdot \frac{E_{iso}}{\phi}$	$F_{ring} = \frac{2\pi}{\sqrt{3}} \cdot t^2 \cdot \sqrt{\frac{E_x \cdot E_y}{1 - \gamma_{xy} \cdot \gamma_{yx}}}$
chessboard local buckling	$\sigma_2 = 0.6 \cdot \alpha \cdot k_2 \cdot \frac{E_{iso}}{\phi}$	$F_{chess} = \frac{2\pi}{\sqrt{3}} \cdot t^2 \cdot \sqrt{\frac{2 \cdot G_{xy} \cdot \sqrt{E_x \cdot E_y}}{1 - \sqrt{\gamma_{xy} \cdot \gamma_{yx}}}}$

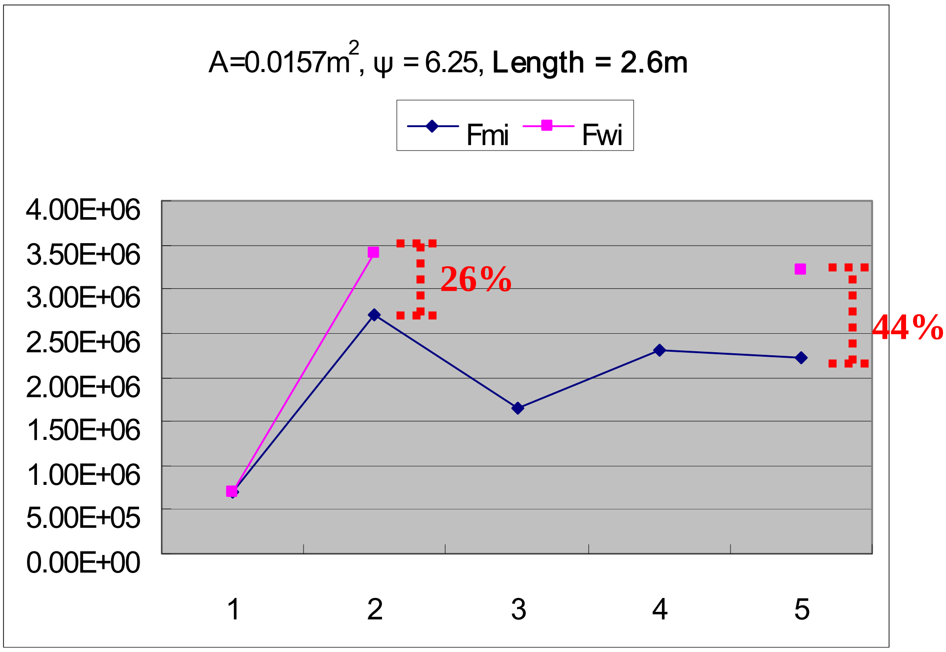
Note: The definite and precise description about each formula is written in Ch 2.5.

First comparison is a set that the cross-section area and shape efficiency value Φ keep constant and the length of the tube varies from 2.6 meters to 7.0 meters. Chart 4.1-1 ~ chart 4.1-9 delineate the calculated results from the two systems of formulae. In these charts, the red lines and dots represent the results from Weaver, which is noted as F_{wi} in charts as well. The blue lines and dots demonstrate the results of Michaeli's formula, which is described as F_{mi} in the charts hereinafter. Digits 1 ~ 5 in X-axis represent various failure modes, which are listed in table 4.1-2. Y-axis refers to the ultimate load of each failure mode and the unit is Newton (N).

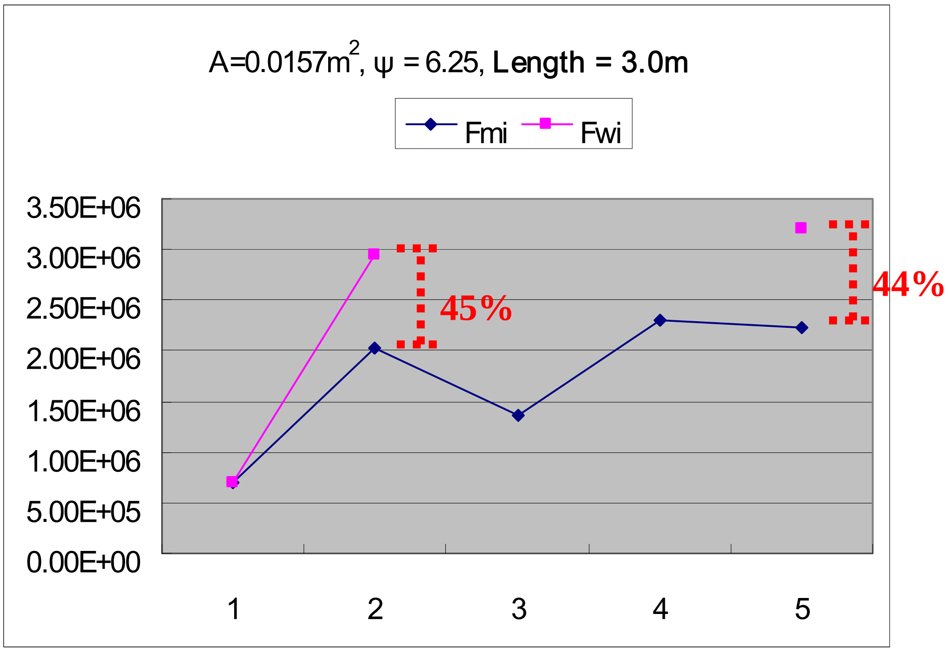
【Table 4.1-2 definition of digits in X-axis of charts】

Digit	Definition
1	ultimate load causing compressive failure
2	critical load of general buckling
3	reduced critical load of general buckling
4	critical load causing ring-like local buckling
5	critical load causing chessboard local buckling

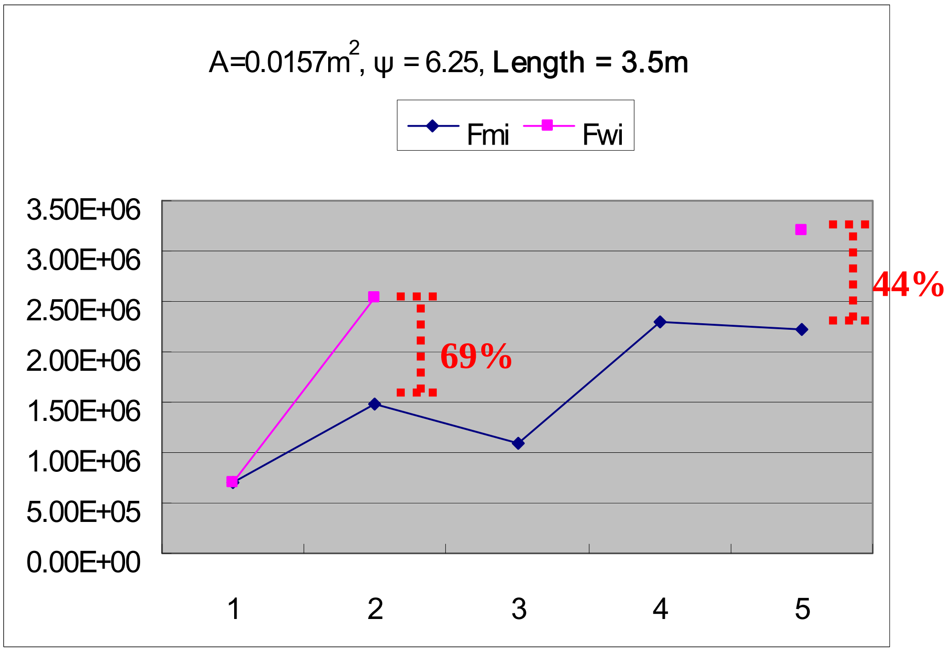
【Chart 4.1-1 Estimated Results from Formulae 1】



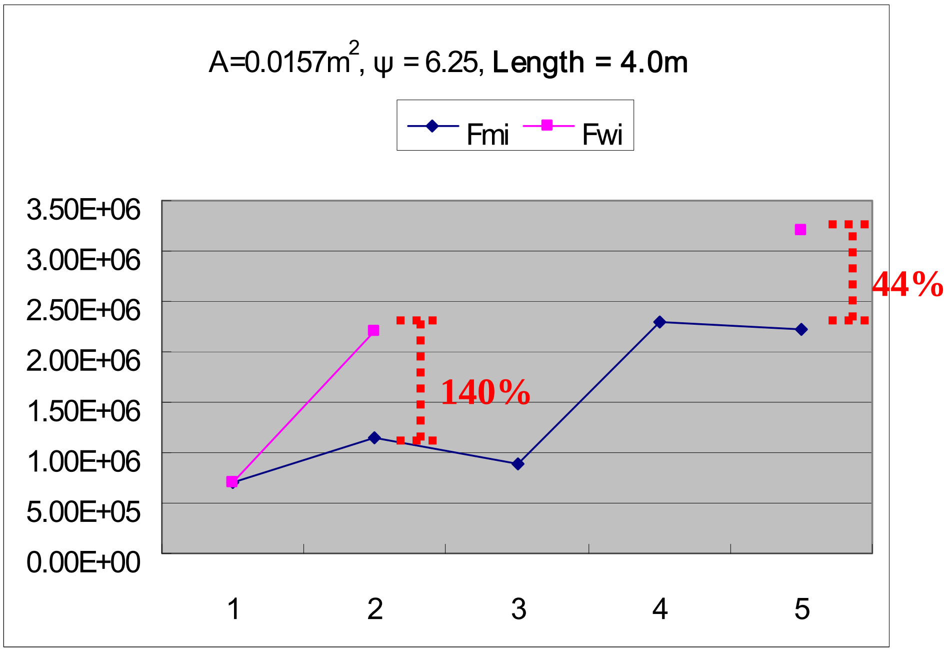
【Chart 4.1-2 Estimated Results from Formulae 2】



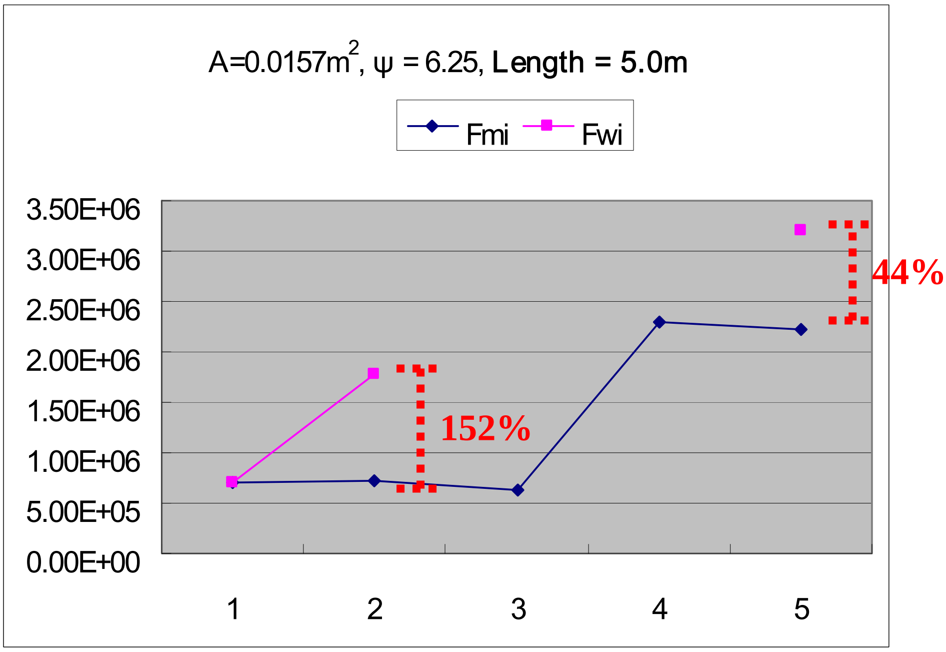
【Chart 4.1-3 Estimated Results from Formulae 3】



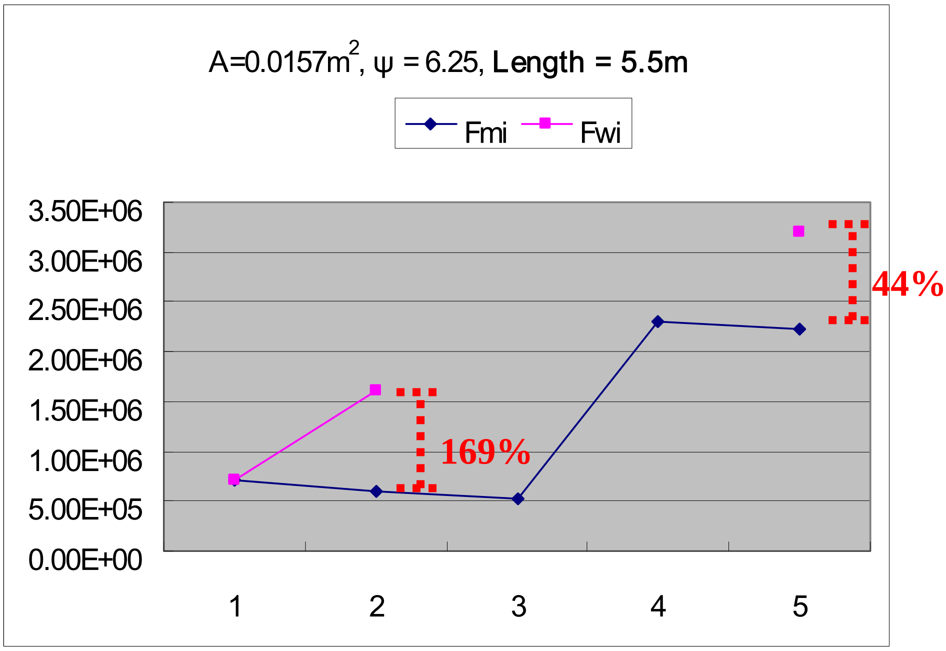
【Chart 4.1-4 Estimated Results from Formulae 4】



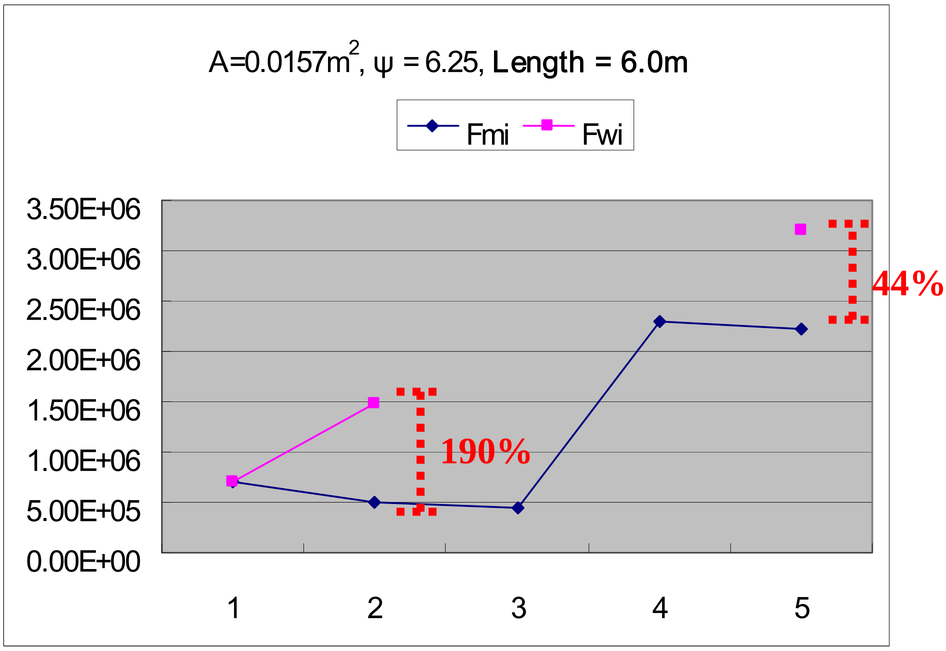
【Chart 4.1-5 Estimated Results from Formulae 5】



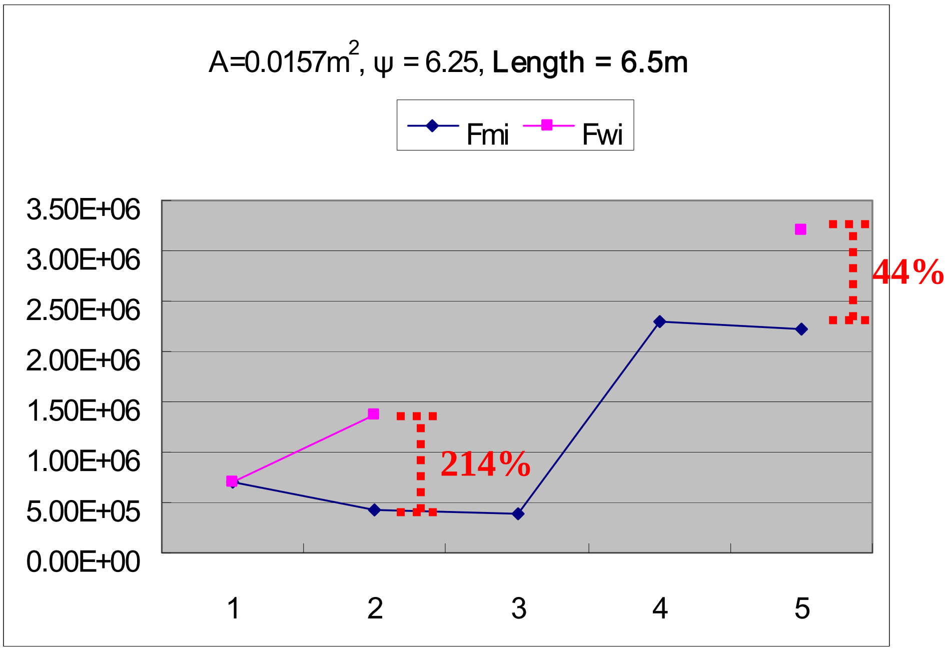
【Chart 4.1-6 Estimated Results from Formulae 6】



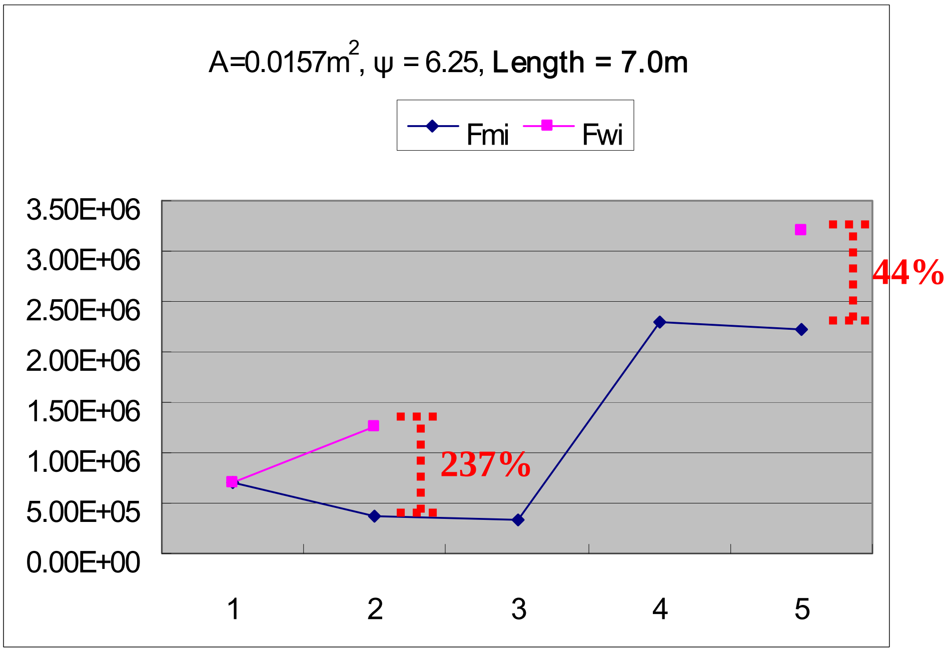
【Chart 4.1-7 Estimated Results from Formulae 7】



【Chart 4.1-8 Estimated Results from Formulae 8】

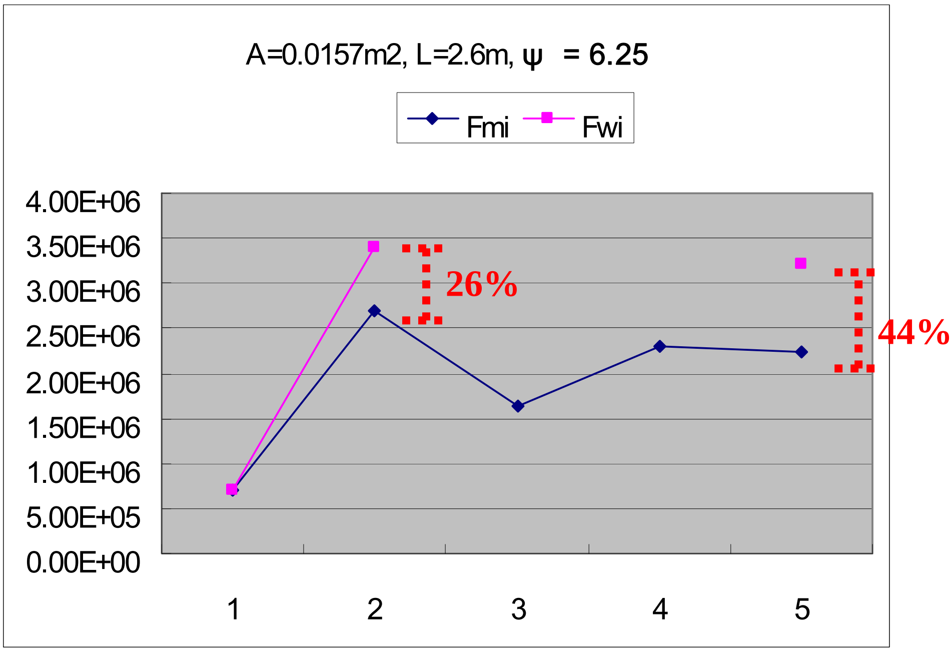


【Chart 4.1-9 Estimated Results from Formulae 9】

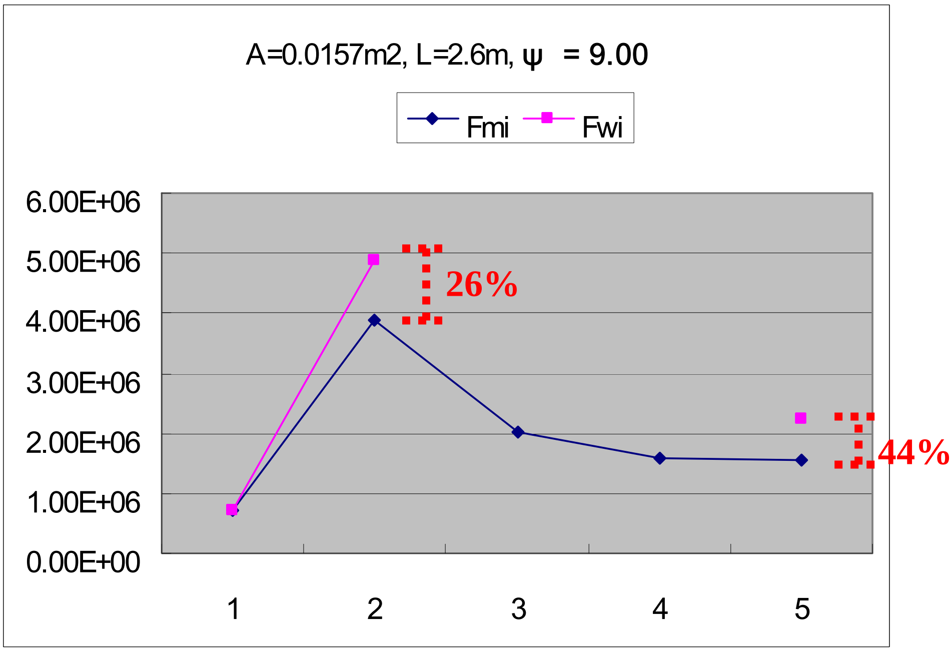


Charts 4.1-10 ~ chart 4.1-18 are the calculated estimated results for various Φ value and constant cross-section area and length.

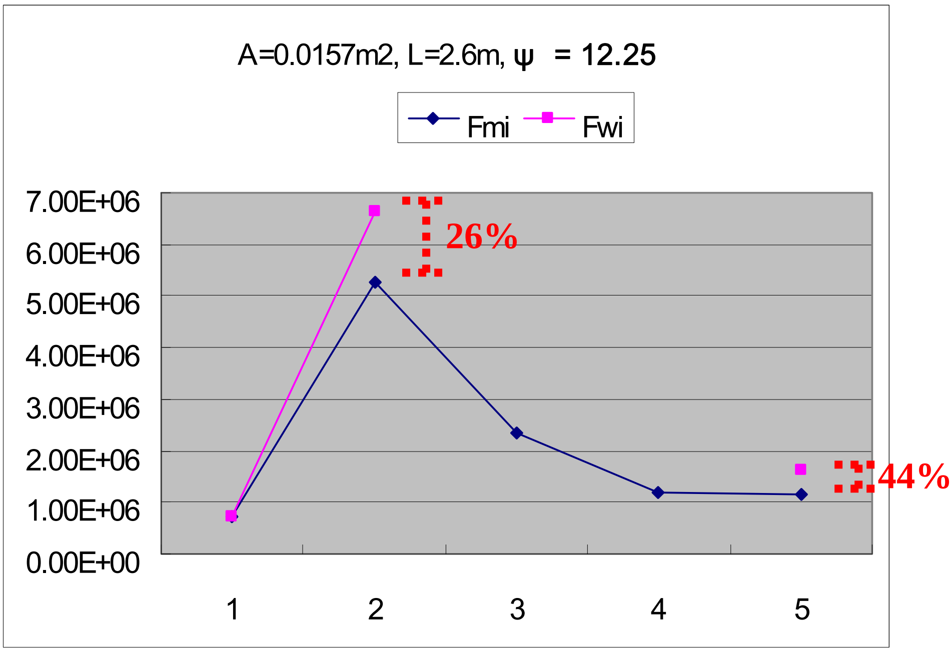
【Chart 4.1-10 Estimated Results from Formulae 10】



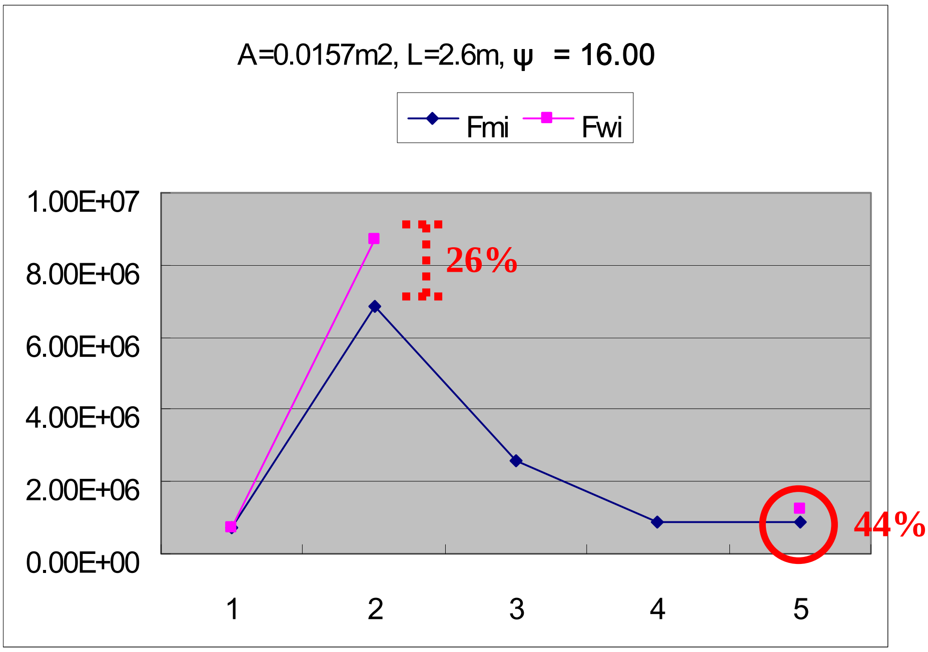
【Chart 4.1-11 Estimated Results from Formulae 11】



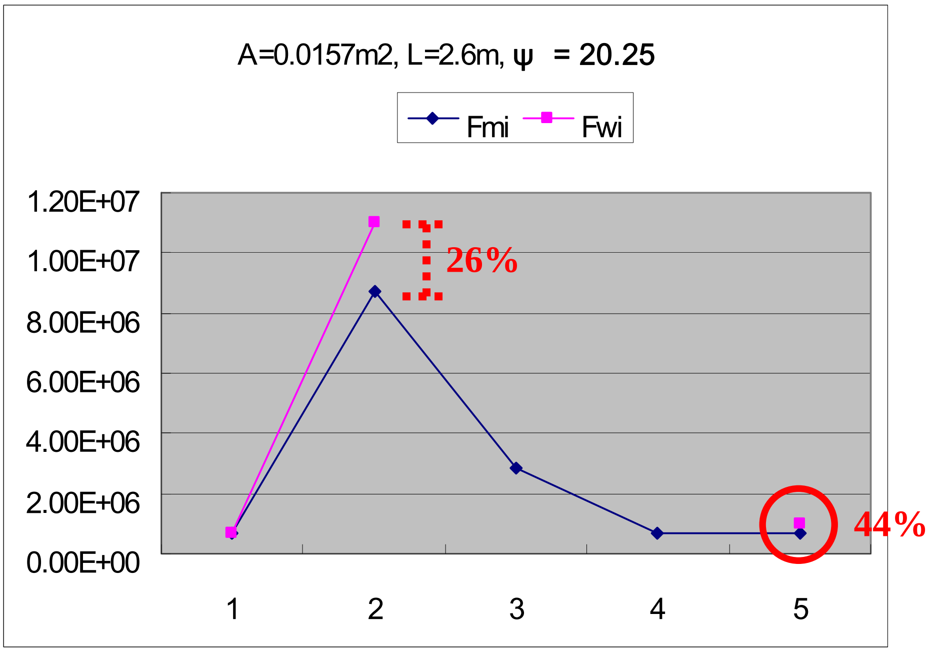
【Chart 4.1-12 Estimated Results from Formulae 12】



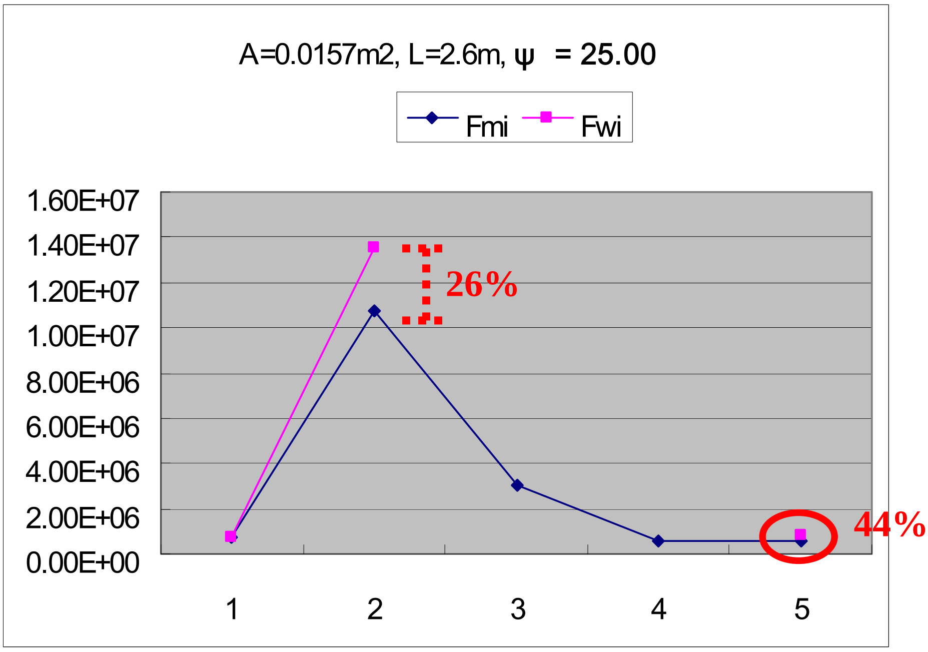
【Chart 4.1-13 Estimated Results from Formulae 13】



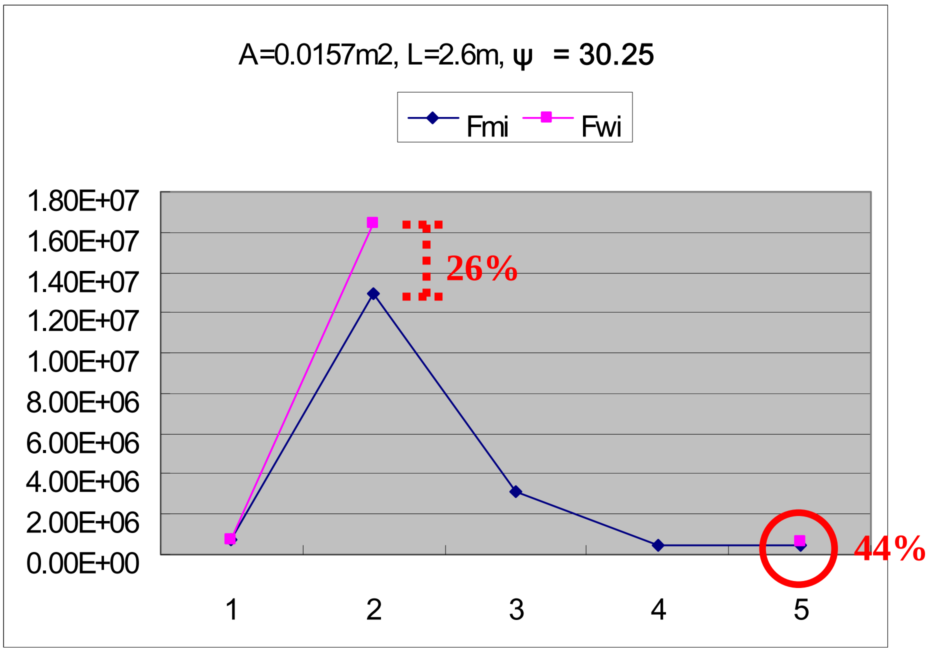
【Chart 4.1-14 Estimated Results from Formulae 14】



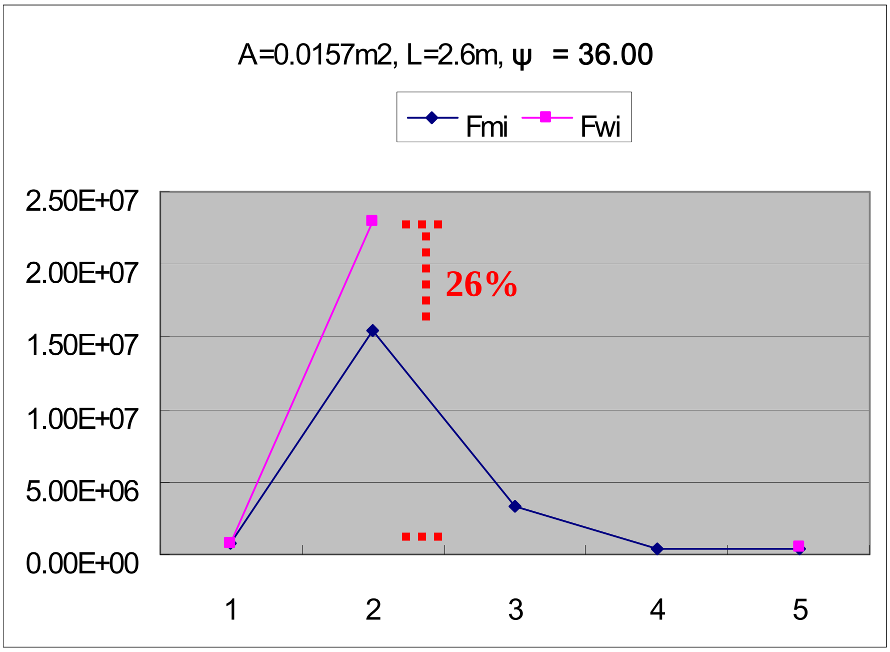
【Chart 4.1-15 Estimated Results from Formulae 15】



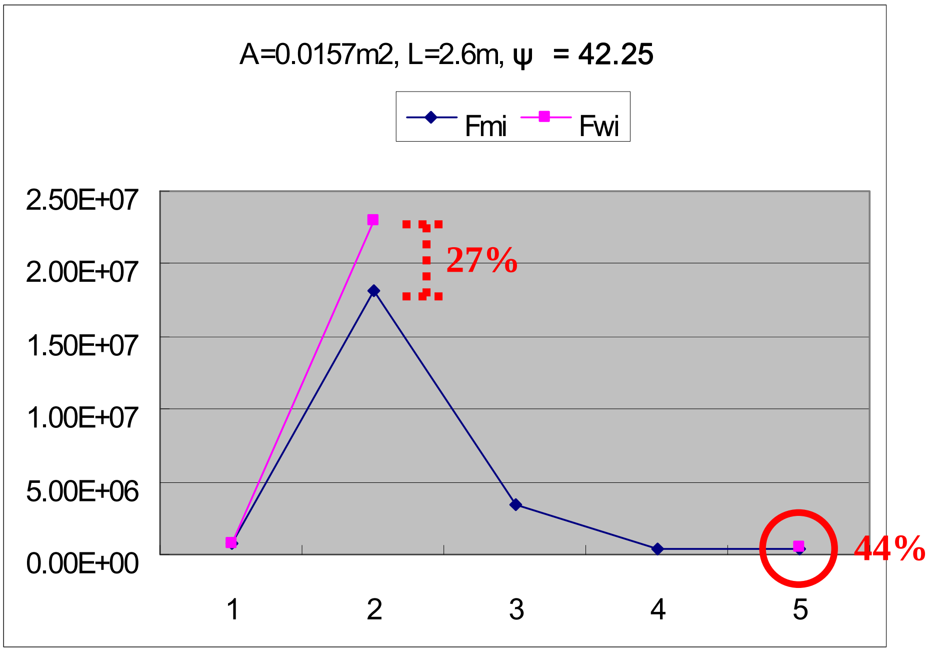
【Chart 4.1-16 Estimated Results from Formulae16】



【Chart 4.1-17 Estimated Results from Formulae 17】



【Chart 4.1-18 Estimated Results from Formulae 18】



Among these assessment results, those from Weaver's formula are always higher than those from Michaeli's.

The result of ultimate compressive load is the same with given geometry because this failure mode is governed by material property of wood and the area of cross-section. The discrepancy of general buckling is about 26% when the length of tube is 2.6 meters. With the increase of the length, the discrepancy is getting higher. In the tube with a length of 7.0 meters, the assessed value of general buckling of Weaver's formula is higher than that of Michaeli's by 237%. Furthermore, among the assigned tubes in comparing framework, the discrepancy in local buckling is around 44% no matter how much the shape efficiency value is.

Since the appraisal results from Michaeli's formula are more conservative than those from Weaver's, the sequential prediction, estimation and evaluation would depend on Michaeli's formula hereafter.

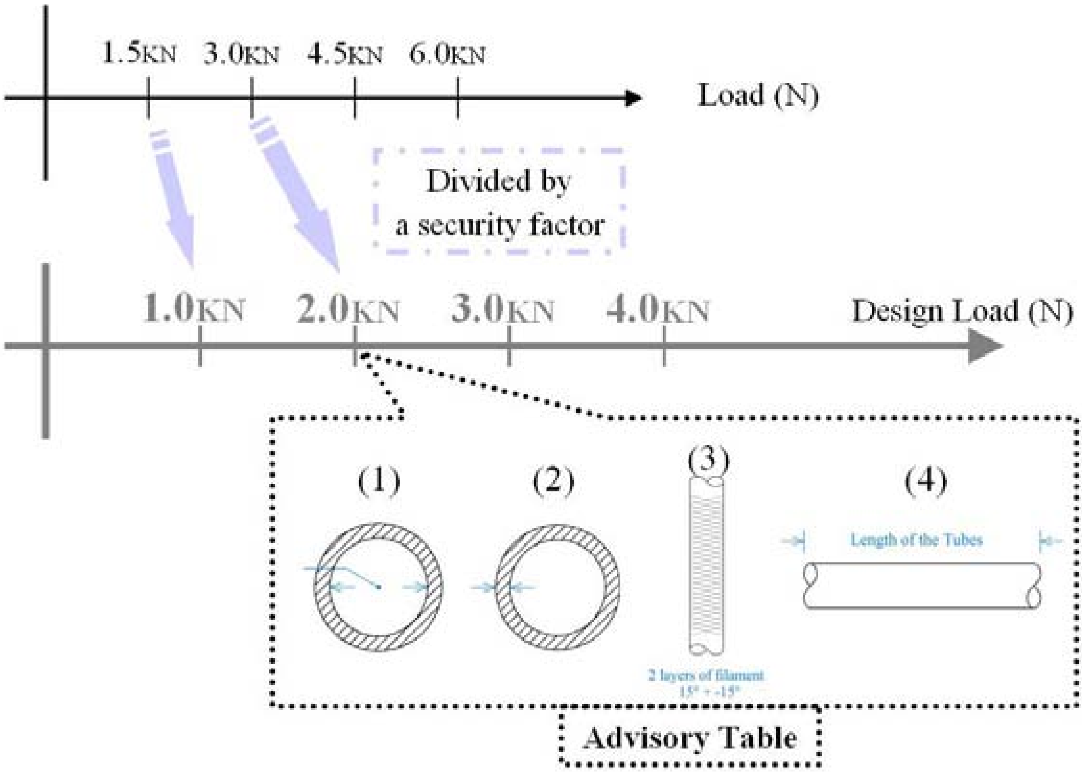


Figure 4.3-1 concept and operational process of advisory table

After the design of a building is completed, the design load for each element could be perceivable by means of structural analysis. Designers or engineers only need to select the feasible tube possessing sufficient capacity to satisfy the structural demand. For application, however, a security factor or a reducing factor is necessary owing to some uncertainty of composite tubes. This research thus picks a reducing factor of 1.5 for consideration of structural safety.

With this security factor of 1.5, when one element is supposed to afford an axial load of X Newton, this element should be designed to take an axial load at least as much as 1.5X Newton. For example, if a column should afford a normal force of 4.0 kilo Newton, the design capacity of it must exceed 6.0 kilo Newton. Engineers or designers have to select a tube depending on the amplified design load in case of uncertainty.

Since the necessary capacity of the tube is obtained, engineers or designers can adopt a feasible one among those plotted in Chapter 4.2, whose profile and capacity have been required according to Michaeli's formula. Procedure of selection relies on the

In these tables, each number for the four geometries is a criterion for certain axial load. These data are minimum requirement. Designers or engineers need to pick a tube whose dimension and geometry are not less than these criteria. In the meanwhile, these advisory tables may offer alternative options for users. A user can choose a tube with larger diameter plus thinner wall or smaller diameter plus thicker wall. Doing so, it can be ensured that the tube can afford the design load and the expected failure mode is supposed to be that plotted in tables.

The designated tubes in this study framework can afford the axial load between 46 kN and 2,400 kN according to the results in Chapter 4.2. After reduced by the security factor of 1.5, the range of the capacity of these tubes is considered between 30 kN and 1,600 kN.

Case study depends on an architectural project in the campus of Technical University of Vienna. The building is design for the department of architecture. According to the project, the requests are listed below:

1> 4~6-storey

2> wood-based construction

3> including working spaces, offices, book shop and studios etc

4> considering evacuation, fire and smoke, structural reliability etc

Figure 4.3-2 site plane and interior plane of first floor -- upper orientation is northern side

Figure 4.3-2 is the plane of the multi-storey timber building and its surroundings. It is obvious that this building is a post-and-beam structure and consists of three rows of columns. Figure 4.3-3 and 4.3-4 are perspectives of the building itself. In these two 3D drawings, the brown volume in the middle is the wooden part while the blue cubes in both sides are composites of steel and reinforced concrete.

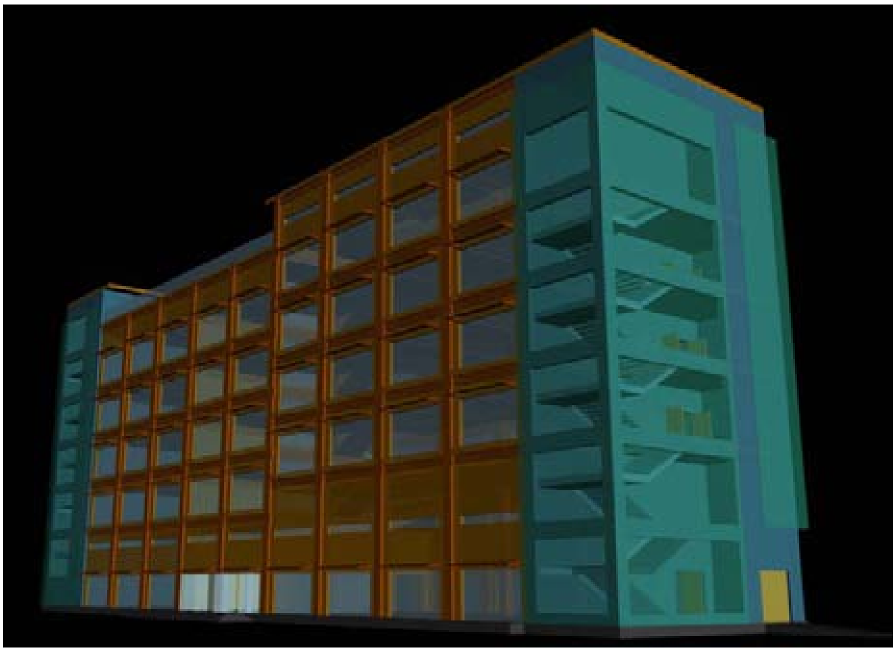


Figure 4.3-3 north-west perspective of the whole building

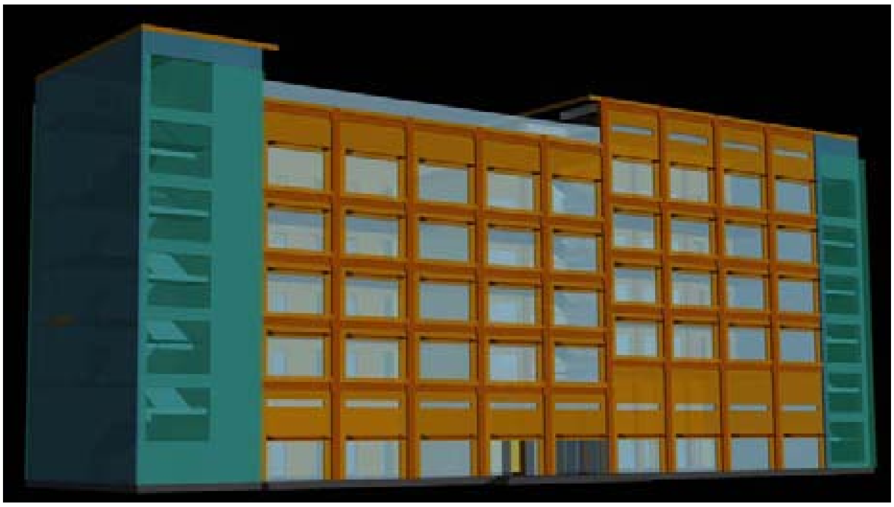


Figure 4.3-4 south-west perspective of the whole building

Sections of the building are illustrated in figure 4.3-5 and figure 4.3-6, which offer a further perspective on the structural system and the arrangement of interior spaces. With a series of decks and staircases in the middle, the whole composite is composed of two parts which are simply 5-storey building connected together.

Figure 4.3-5 section of the building -- left hand side is east and the other is west

Figure 4.3-6 section of the building -- left hand side is west and the other is east

In order to calculate the area and vertical load afforded by one single column, a plane as shown in figure 4.3-7 is provided. Columns located in the middle row have to take most vertical load from floor. Owing to wood D70 as the material of floor, dead load from the floor whose density is 10.8 kN/m3 and thickness is 30 cm would be 3.5 kN/m2. Depending on Eurocode 5, the live load is set as 5.0 kN/m2 because it is a public space with collected crowd. The vertical load is thus 8.5 kN/m2 from floors.

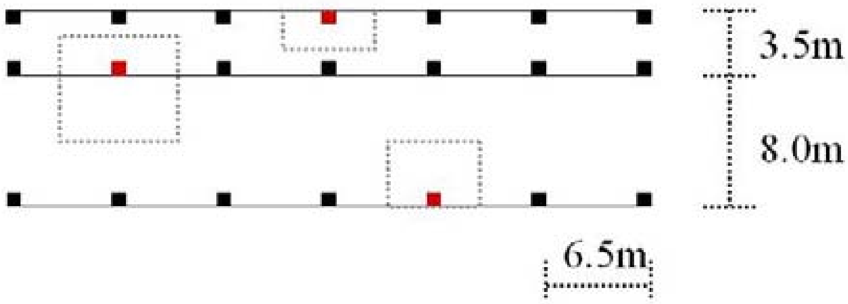


Figure 4.3-7 arrangement of columns and the area afforded by single column

As shown in figure 4.3-7, the columns in the middle row take charge of a floor around 40 square meters. So, the columns here are supposed to afford vertical loads as much as 340 kN. However, if a column only needs to afford a roof without crowd over it, the loading will be 140 kN because live load is not necessary to be considered.

On this fundament, it can be declared that the load taken by one column varied with the composition of the building as shown below:
1> 1-storey building => 140 kN
2> 2-storey building => 480 kN (140 + 340*1)
3> 3-storey building => 820 kN (140 + 340*2)
4> 4-storey building => 1,160 kN (140 + 340*3)
5> 5-storey building => 1,500 kN (140 + 340*4)

As demonstrated previously, the maximum capacity of tubes assigned in this research, which has been reduced, is around 1,600kN. It could be asserted that these tubes are serviceable for such a design complex shown in this paragraph. In the other hand, a building analogous to the project shown in this paragraph may adopt the tubes designated in this framework.

4.5 Optimal Profiles of Tubes

As explained in Ch 3.5, the way to find out the optimal profile for a tube subjected to certain load is to conceive from the formula and select a dominant factor for each failure mode. Figure 4.5-1 illustrates the philosophy and concept to find out governing factor for three failure modes.

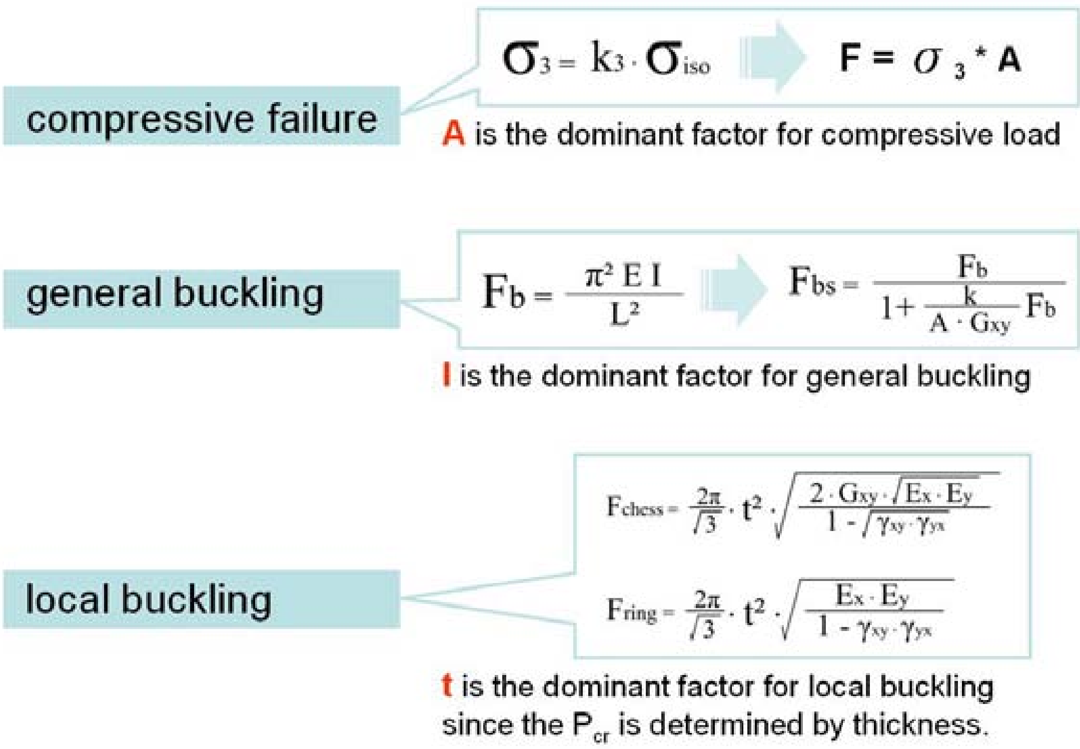


Figure 4.5-1 concept and thinking process for dominant factor of certain failure mode

With given material and design requirement, the ultimate load causing compressive failure can be approached by adjusting the area of cross-section. In the meanwhile, moment inertia, I value, is the dominating factor for approaching general buckling. Although some parameters still need to be considered, they are less significant as moment inertia is. Thus this research simply takes moment inertia I as the dominant variable for critical general bucking load. Finally, the ultimate load for local buckling is thickness of wooden wall. In spit of other parameters like elastic module, shear module and poison ration existing in the formula, their values would be determined while the thickness is fixed. It thus can be asserted that thickness is the dominating variable for local buckling and others are subsequence of the thickness.

According to the building model discussed in Ch 4.4 and analyzed by RSTAB, the column which needs to afford highest axial load is in the ground floor and has to afford about 1,030 kN.　The results are depicted in figure 4.5-2 and 4.5-3.

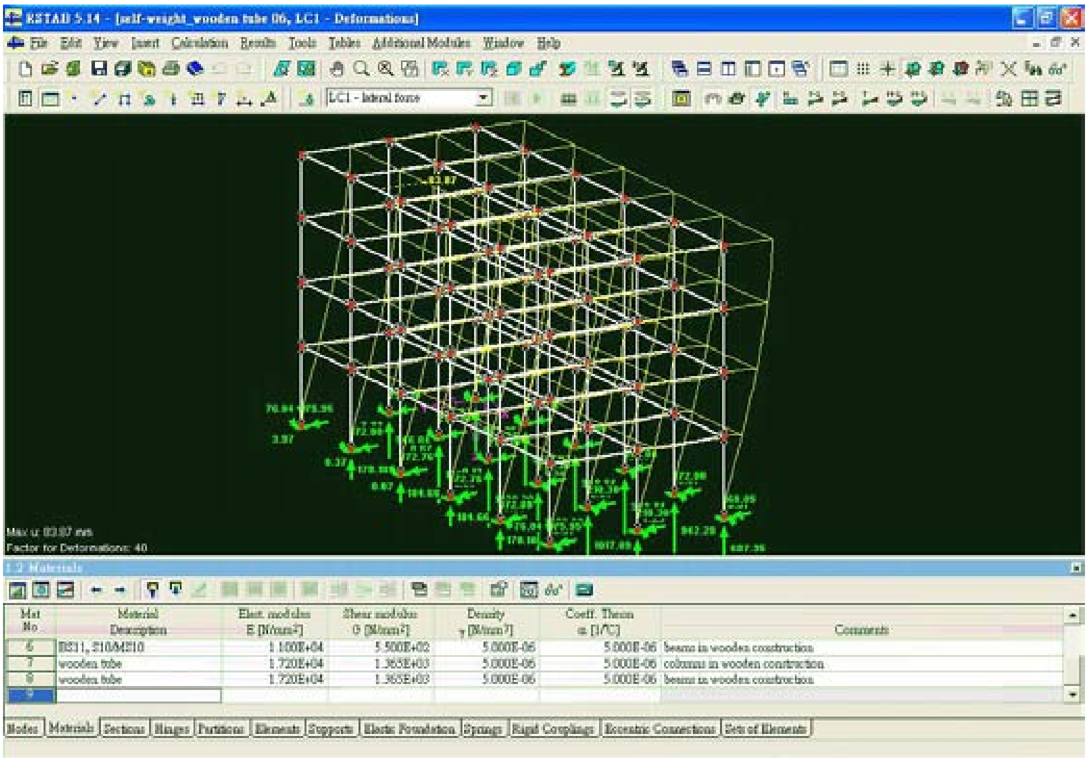


Figure 4.5-2 calculated results be means of RSTAB

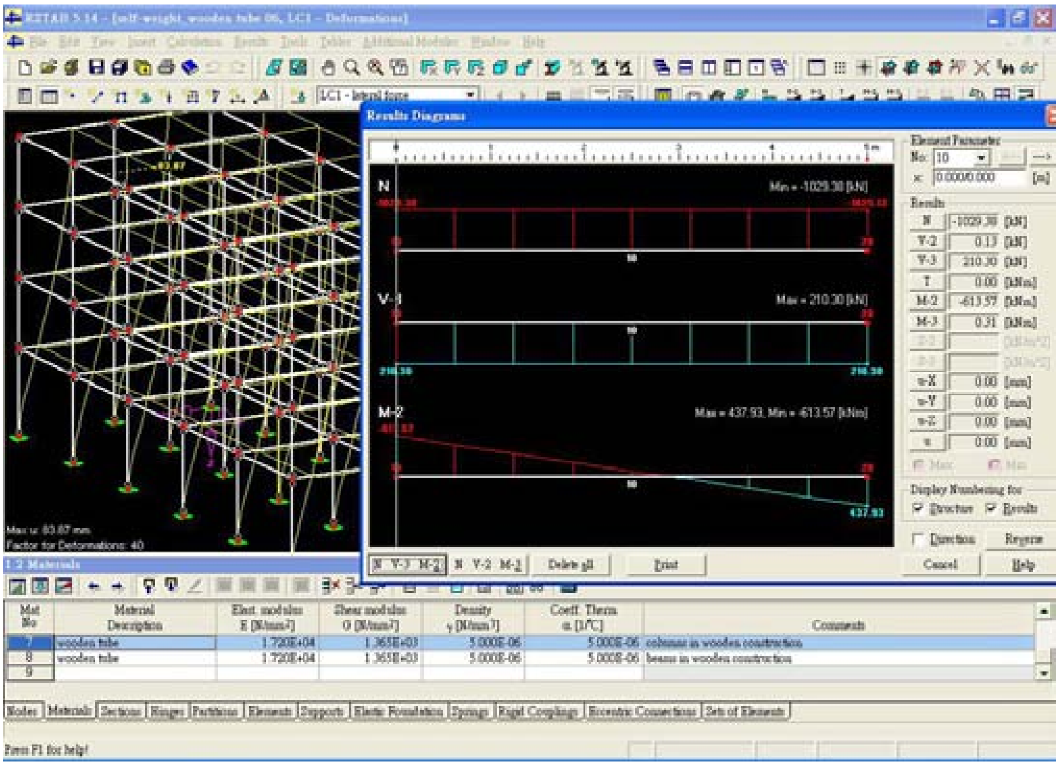
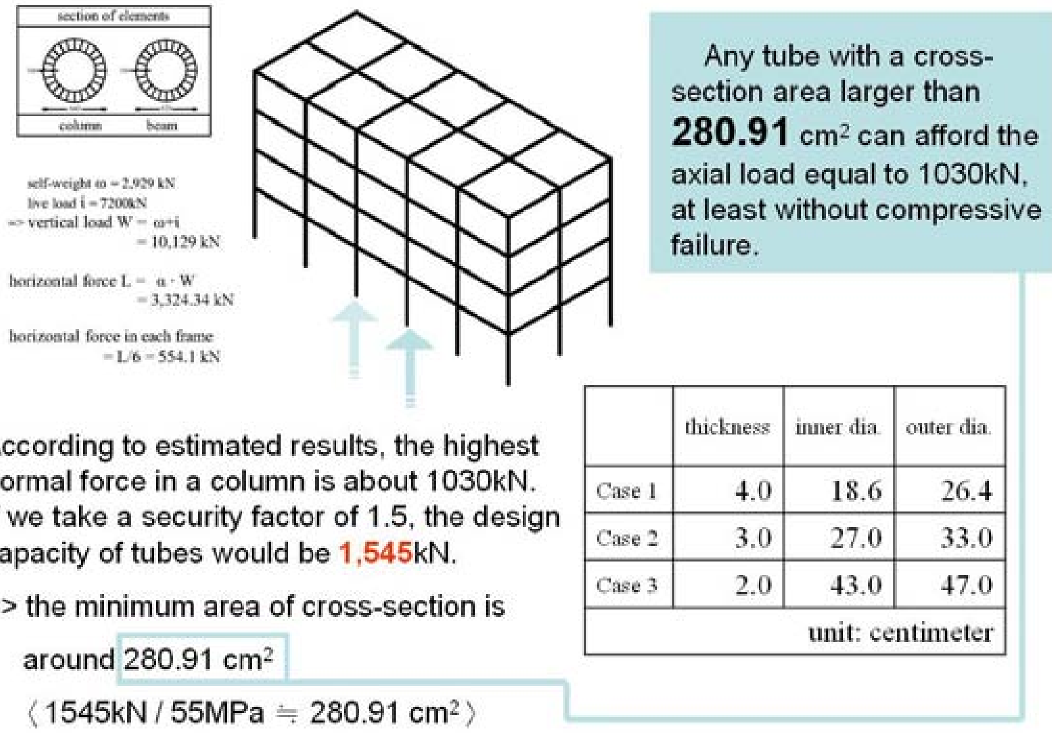


Figure 4.5-3 maximum axial load in this wooden tube construction model

Considering the security factor of 1.5 used in Ch 4.2 and 4.3, the design load should be set as 1,545 kN. This means that designers are supposed to find a tube whose capacity is higher than 1,545 kN to bear such axial loading.

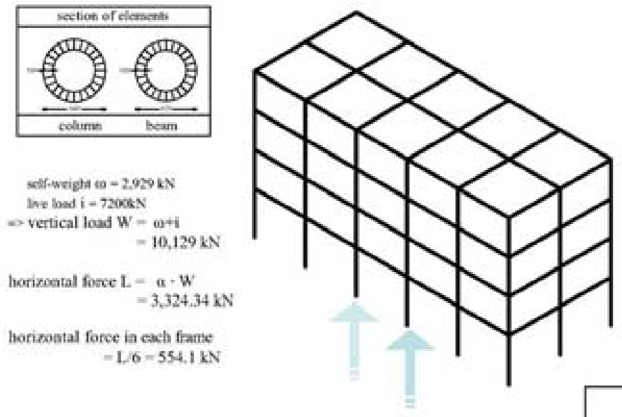
Figure 4.5-4 demonstrates the procedure to find out the cross-sectional area for the ultimate load resulting in compressive failure mode. In the meanwhile, this framework provides alternative possibilities which can achieve the same target, which are plotted in bottom-right corner. This declares that the potential solution is not unique.



	thickness	inner dia.	outer dia.
Case 1	4.0	18.6	26.4
Case 2	3.0	27.0	33.0
Case 3	2.0	43.0	47.0
			unit: centimeter

Figure 4.5-4 procedure of searching for proper area to approach ultimate compressive load

For the same reason, appropriate moment inertia for approaching general buckling is shown in figure 4.5-5. After the value of moment inertia become available, the substitute choices are listed. Once again, the solution is not unique either.



With a given length, any tube with a sectional moment inertia higher than **24863.5** cm^4 can afford the axial load equal to 1545kN, at least without general buckling.

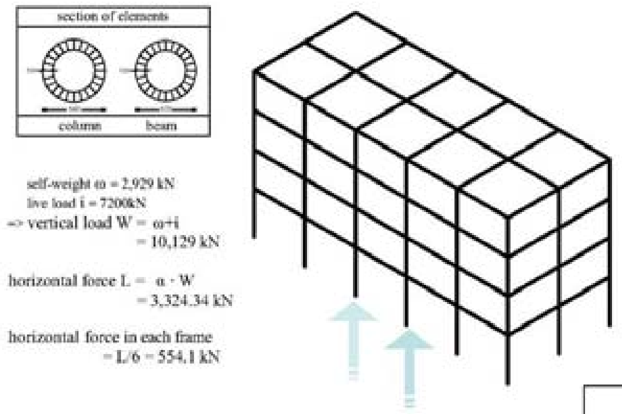
According to estimated results, the highest normal force in a column is about 1030kN. If we take a security factor of 1.5, the design capacity of tubes would be **1,545**kN.

=> the minimum moment inertia is around

24863.5 cm^4

	thickness	inner dia.	outer dia.
Case 1	4.0	20.9	28.9
Case 2	3.0	24.6	30.6
Case 3	2.0	29.9	33.9
length: 500 unit: centimeter			

Figure 4.5-5 procedure of searching for moment inertia for critical general buckling load



Any tube with a wall thicker than **1.00** cm can afford the axial load equal to 1030kN, at least without compressive failure.

According to estimated results, the highest normal force in a column is about 1030kN. If we take a security factor of 1.5, the design capacity of tubes would be **1,545**kN.

=> the minimum thickness of the wall is

around 1.00 cm

	thickness	inner dia.	outer dia.
Case 1	1.00	25.0	27.0
Case 2	1.00	50.0	52.0
Case 3	1.00	60.0	62.0
unit: centimeter			

Figure 4.5-6 procedure of searching for thickness for critical local buckling load

Appropriate thickness for approaching critical local buckling load is illustrated in figure 4.5-6.

If the three controlling factors could be adjusted simultaneously to the necessary criteria, the optimal profile for a tube subjected to assigned load is found. In practical operation, however, it is almost impossible to adjust all of them simultaneously. Most likely, only two of these factors can be adjusted as users wish at one time. Therefore, the task for this research framework is to select the relatively significant parameters for the target of optimized profile.

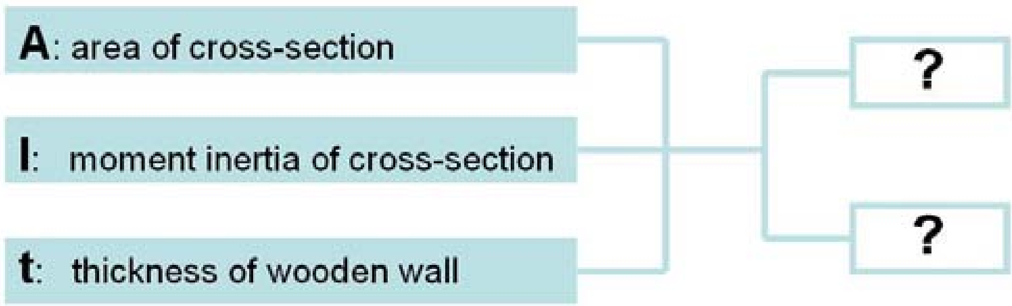


Figure 4.5-7 contradiction for achieving an optimal profile

Among these three factors, users can only adjust two and approach only two critical loads of failure modes at the same time. Thus, it is necessary to eliminate one of the most useless factors. If this factor is not really decisive or significant, it can be ignored in the estimation.

The local buckling occurs only when the wall is very thin. In practical engineering, it is impossible to adopt such a thin wall. If the wall is too thin, any subtle crack may extremely reduce the capacity. Since thin wall is impossible to apply, it is not necessary to consider local buckling in practice.

Generally, the wall of a tube should be thick to eliminate the influence of crack or any defect of wood. Furthermore, the ultimate load of local buckling in a tube with thick wall is usually significantly higher than the critical load for general buckling and compression. Therefore, local buckling seldom occurs in practical engineering and it is not necessary to concern it. Coincidently, this conclusion corresponds the inference derived on Ch 4.2. See page 4-13.

4.2 Ultimate Load and Dominant Failure Mode

The appraisal capacity for axial load of each tube is listed in table 4.2-1-a ~ table 4.2-24-c.

In one table, the inner diameter and thickness of the wall are annotated in the title and end. All tubes plotted in one table possess the same diameter and thickness. The column in left side is the scheme of filament reinforcement, which comprises two layers. The second row shows the length of tubes. The lowest ultimate loads among three failure modes, which are taken as the capacity of tubes, are written in ways of Newton.

Colors in the frames refer to the failure mode. Blank frames mean that the dominant failure mode is general/elastic/Eular buckling. Light-gray frames indicate that the governing failure mode is compressive failure, which contains crack, crumble or split etc. Dark-gray frames state that the failure mode occurring firstly is local buckling. Generally speaking, ultimate load for chessboard local buckling is lower than that of ring-like buckling. Among the assumed tubes, however, no local buckling occurs. This demonstrates that the critical load of local buckling is higher than others and may be not significant in composite wooden tubes with common dimension. This deductive conclusion correspond the inference acquired in Ch 4.5. See page 4-72.

【Table 4.2-1-a ultimate loads of tubes -- thickness 2cm / inner diameter 10cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	3.39E+05	2.93E+05	2.48E+05	2.13E+05	1.84E+05	1.61E+05	1.42E+05
30°+60°	3.39E+05	2.92E+05	2.47E+05	2.11E+05	1.83E+05	1.60E+05	1.41E+05
45°+45°	3.39E+05	2.92E+05	2.46E+05	2.11E+05	1.83E+05	1.60E+05	1.41E+05
10°+10°	3.39E+05	2.99E+05	2.53E+05	2.17E+05	1.88E+05	1.64E+05	1.45E+05
15°+15°	3.39E+05	2.98E+05	2.52E+05	2.16E+05	1.87E+05	1.64E+05	1.44E+05
30°+30°	3.39E+05	2.95E+05	2.50E+05	2.14E+05	1.85E+05	1.62E+05	1.42E+05
60°+60°	3.39E+05	2.89E+05	2.44E+05	2.09E+05	1.81E+05	1.58E+05	1.39E+05
75°+75°	3.39E+05	2.87E+05	2.43E+05	2.08E+05	1.80E+05	1.58E+05	1.39E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 10 cm

【Table 4.2-1-b ultimate loads of tubes -- thickness 2cm / inner diameter 10cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.26E+05	1.13E+05	1.01E+05	9.15E+04	8.31E+04	7.58E+04
30°+60°	1.25E+05	1.12E+05	1.00E+05	9.08E+04	8.24E+04	7.52E+04
45°+45°	1.25E+05	1.11E+05	1.00E+05	9.05E+04	8.22E+04	7.50E+04
10°+10°	1.28E+05	1.15E+05	1.03E+05	9.33E+04	8.47E+04	7.73E+04
15°+15°	1.28E+05	1.14E+05	1.03E+05	9.30E+04	8.44E+04	7.70E+04
30°+30°	1.26E+05	1.13E+05	1.02E+05	9.18E+04	8.34E+04	7.60E+04
60°+60°	1.24E+05	1.10E+05	9.93E+04	8.98E+04	8.15E+04	7.43E+04
75°+75°	1.23E+05	1.10E+05	9.90E+04	8.95E+04	8.13E+04	7.41E+04

unit: Newton (N)
thickness: 2 cm
inner diameter: 10 cm

【Table 4.2-1-c ultimate loads of tubes -- thickness 2cm / inner diameter 10cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	6.94E+04	6.38E+04	5.88E+04	5.44E+04	5.05E+04	4.70E+04
30°+60°	6.88E+04	6.33E+04	5.83E+04	5.40E+04	5.01E+04	4.66E+04
45°+45°	6.87E+04	6.31E+04	5.82E+04	5.38E+04	4.99E+04	4.65E+04
10°+10°	7.08E+04	6.51E+04	6.00E+04	5.55E+04	5.15E+04	4.79E+04
15°+15°	7.05E+04	6.48E+04	5.98E+04	5.53E+04	5.13E+04	4.78E+04
30°+30°	6.96E+04	6.40E+04	5.90E+04	5.46E+04	5.06E+04	4.71E+04
60°+60°	6.81E+04	6.26E+04	5.77E+04	5.34E+04	4.95E+04	4.61E+04
75°+75°	6.79E+04	6.24E+04	5.76E+04	5.32E+04	4.94E+04	4.60E+04

unit: Newton (N)
thickness: 2 cm
inner diameter: 10 cm

【Table 4.2-2-a ultimate loads of tubes -- thickness 2cm / inner diameter 14cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.23E+05	3.70E+05	3.27E+05
30°+60°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.21E+05	3.69E+05	3.25E+05
45°+45°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.20E+05	3.68E+05	3.25E+05
10°+10°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.31E+05	3.78E+05	3.33E+05
15°+15°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.30E+05	3.77E+05	3.33E+05
30°+30°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.25E+05	3.73E+05	3.29E+05
60°+60°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.16E+05	3.65E+05	3.22E+05
75°+75°	4.52E+05	4.52E+05	4.52E+05	4.52E+05	4.14E+05	3.63E+05	3.20E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 14 cm

【Table 4.2-2-b ultimate loads of tubes -- thickness 2cm / inner diameter 14cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	2.91E+05	2.60E+05	2.34E+05	2.12E+05	1.93E+05	1.76E+05
30°+60°	2.89E+05	2.59E+05	2.33E+05	2.11E+05	1.91E+05	1.75E+05
45°+45°	2.89E+05	2.58E+05	2.32E+05	2.10E+05	1.91E+05	1.74E+05
10°+10°	2.97E+05	2.66E+05	2.39E+05	2.16E+05	1.97E+05	1.79E+05
15°+15°	2.96E+05	2.65E+05	2.38E+05	2.16E+05	1.96E+05	1.79E+05
30°+30°	2.92E+05	2.62E+05	2.36E+05	2.13E+05	1.94E+05	1.77E+05
60°+60°	2.86E+05	2.56E+05	2.30E+05	2.08E+05	1.89E+05	1.73E+05
75°+75°	2.85E+05	2.55E+05	2.30E+05	2.08E+05	1.89E+05	1.72E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 14 cm

【Table 4.2-2-c ultimate loads of tubes -- thickness 2cm / inner diameter 14cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.61E+05	1.48E+05	1.37E+05	1.27E+05	1.18E+05	1.09E+05
30°+60°	1.60E+05	1.47E+05	1.36E+05	1.26E+05	1.17E+05	1.09E+05
45°+45°	1.60E+05	1.47E+05	1.36E+05	1.25E+05	1.16E+05	1.08E+05
10°+10°	1.64E+05	1.51E+05	1.40E+05	1.29E+05	1.20E+05	1.12E+05
15°+15°	1.64E+05	1.51E+05	1.39E+05	1.29E+05	1.20E+05	1.11E+05
30°+30°	1.62E+05	1.49E+05	1.37E+05	1.27E+05	1.18E+05	1.10E+05
60°+60°	1.58E+05	1.46E+05	1.34E+05	1.24E+05	1.15E+05	1.07E+05
75°+75°	1.58E+05	1.45E+05	1.34E+05	1.24E+05	1.15E+05	1.07E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 14 cm

【Table 4.2-3-a ultimate loads of tubes -- thickness 2cm / inner diameter 18cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05
30°+60°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05
45°+45°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05
10°+10°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05
15°+15°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05
30°+30°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05
60°+60°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05
75°+75°	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05	5.65E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 18 cm

【Table 4.2-3-b ultimate loads of tubes -- thickness 2cm / inner diameter 18cm】

	$Long_{2\text{-}7}$	$Long_{2\text{-}8}$	$Long_{2\text{-}9}$	$Long_{2\text{-}10}$	$Long_{2\text{-}11}$	$Long_{2\text{-}12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	5.55E+05	4.98E+05	4.49E+05	4.07E+05	3.70E+05	3.38E+05
30°+60°	5.53E+05	4.96E+05	4.47E+05	4.05E+05	3.68E+05	3.36E+05
45°+45°	5.52E+05	4.95E+05	4.46E+05	4.04E+05	3.67E+05	3.36E+05
10°+10°	5.65E+05	5.08E+05	4.58E+05	4.15E+05	3.77E+05	3.45E+05
15°+15°	5.65E+05	5.06E+05	4.56E+05	4.14E+05	3.76E+05	3.44E+05
30°+30°	5.59E+05	5.01E+05	4.52E+05	4.09E+05	3.72E+05	3.40E+05
60°+60°	5.47E+05	4.90E+05	4.42E+05	4.00E+05	3.64E+05	3.32E+05
75°+75°	5.44E+05	4.88E+05	4.40E+05	3.98E+05	3.63E+05	3.31E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 18 cm

【Table 4.2-3-c ultimate loads of tubes -- thickness 2cm / inner diameter 18cm】

	$Long_{2\text{-}13}$	$Long_{2\text{-}14}$	$Long_{2\text{-}15}$	$Long_{2\text{-}16}$	$Long_{2\text{-}17}$	$Long_{2\text{-}18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	3.10E+05	2.86E+05	2.64E+05	2.44E+05	2.27E+05	2.11E+05
30°+60°	3.08E+05	2.84E+05	2.62E+05	2.43E+05	2.25E+05	2.10E+05
45°+45°	3.08E+05	2.83E+05	2.61E+05	2.42E+05	2.25E+05	2.09E+05
10°+10°	3.16E+05	2.91E+05	2.69E+05	2.49E+05	2.31E+05	2.15E+05
15°+15°	3.15E+05	2.90E+05	2.68E+05	2.48E+05	2.31E+05	2.15E+05
30°+30°	3.12E+05	2.87E+05	2.65E+05	2.45E+05	2.28E+05	2.12E+05
60°+60°	3.05E+05	2.81E+05	2.59E+05	2.40E+05	2.23E+05	2.07E+05
75°+75°	3.04E+05	2.80E+05	2.58E+05	2.39E+05	2.22E+05	2.07E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 18 cm

【Table 4.2-4-a ultimate loads of tubes -- thickness 2cm / inner diameter 22cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05
30°+60°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05
45°+45°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05
10°+10°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05
15°+15°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05
30°+30°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05
60°+60°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05
75°+75°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.78E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 22 cm

【Table 4.2-4-b ultimate loads of tubes -- thickness 2cm / inner diameter 22cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.29E+05	5.75E+05
30°+60°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.26E+05	5.73E+05
45°+45°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.25E+05	5.72E+05
10°+10°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.41E+05	5.86E+05
15°+15°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.39E+05	5.85E+05
30°+30°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.33E+05	5.79E+05
60°+60°	6.78E+05	6.78E+05	6.78E+05	6.78E+05	6.19E+05	5.66E+05
75°+75°	6.78E+05	6.78E+05	6.78E+05	6.76E+05	6.16E+05	5.64E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 22 cm

【Table 4.2-4-c ultimate loads of tubes -- thickness 2cm / inner diameter 22cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	5.28E+05	4.87E+05	4.50E+05	4.17E+05	3.87E+05	3.61E+05
30°+60°	5.26E+05	4.84E+05	4.47E+05	4.14E+05	3.85E+05	3.59E+05
45°+45°	5.25E+05	4.83E+05	4.46E+05	4.14E+05	3.84E+05	3.58E+05
10°+10°	5.38E+05	4.96E+05	4.59E+05	4.25E+05	3.95E+05	3.68E+05
15°+15°	5.37E+05	4.95E+05	4.57E+05	4.24E+05	3.94E+05	3.67E+05
30°+30°	5.31E+05	4.89E+05	4.52E+05	4.19E+05	3.89E+05	3.63E+05
60°+60°	5.20E+05	4.79E+05	4.42E+05	4.10E+05	3.81E+05	3.55E+05
75°+75°	5.17E+05	4.77E+05	4.41E+05	4.08E+05	3.79E+05	3.53E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 22 cm

【Table 4.2-5-a ultimate loads of tubes -- thickness 2cm / inner diameter 26cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
30°+60°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
45°+45°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
10°+10°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
15°+15°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
30°+30°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
60°+60°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
75°+75°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 26 cm

【Table 4.2-5-b ultimate loads of tubes -- thickness 2cm / inner diameter 26cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
30°+60°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
45°+45°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
10°+10°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
15°+15°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
30°+30°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
60°+60°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05
75°+75°	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05	7.91E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 26 cm

【Table 4.2-5-c ultimate loads of tubes -- thickness 2cm / inner diameter 26cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	7.91E+05	7.61E+05	7.04E+05	6.54E+05	6.08E+05	5.67E+05
30°+60°	7.91E+05	7.58E+05	7.01E+05	6.50E+05	6.05E+05	5.64E+05
45°+45°	7.91E+05	7.57E+05	7.00E+05	6.49E+05	6.04E+05	5.63E+05
10°+10°	7.91E+05	7.76E+05	7.18E+05	6.66E+05	6.20E+05	5.78E+05
15°+15°	7.91E+05	7.75E+05	7.16E+05	6.65E+05	6.18E+05	5.76E+05
30°+30°	7.91E+05	7.67E+05	7.09E+05	6.58E+05	6.11E+05	5.70E+05
60°+60°	7.91E+05	7.50E+05	6.94E+05	6.43E+05	5.98E+05	5.57E+05
75°+75°	7.91E+05	7.46E+05	6.90E+05	6.40E+05	5.96E+05	5.55E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 26 cm

【Table 4.2-6-a ultimate loads of tubes -- thickness 2cm / inner diameter 30cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
30°+60°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
45°+45°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
10°+10°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
15°+15°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
30°+30°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
60°+60°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
75°+75°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 30 cm

【Table 4.2-6-b ultimate loads of tubes -- thickness 2cm / inner diameter 30cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
30°+60°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
45°+45°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
10°+10°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
15°+15°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
30°+30°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
60°+60°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05
75°+75°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 30 cm

【Table 4.2-6-c ultimate loads of tubes -- thickness 2cm / inner diameter 30cm】

	$Long_{2\text{-}13}$	$Long_{2\text{-}14}$	$Long_{2\text{-}15}$	$Long_{2\text{-}16}$	$Long_{2\text{-}17}$	$Long_{2\text{-}18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	8.96E+05	8.36E+05
30°+60°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	8.92E+05	8.32E+05
45°+45°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	8.91E+05	8.31E+05
10°+10°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	8.52E+05
15°+15°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.04E+05	8.50E+05
30°+30°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	9.02E+05	8.41E+05
60°+60°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	8.83E+05	8.23E+05
75°+75°	9.04E+05	9.04E+05	9.04E+05	9.04E+05	8.78E+05	8.19E+05

unit: Newton (N)
thickness: 2 cm
inner diameter: 30 cm

【Table 4.2-7-a ultimate loads of tubes -- thickness 2cm / inner diameter 34cm】

	$Long_{2\text{-}0}$	$Long_{2\text{-}1}$	$Long_{2\text{-}2}$	$Long_{2\text{-}3}$	$Long_{2\text{-}4}$	$Long_{2\text{-}5}$	$Long_{2\text{-}6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
30°+60°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
45°+45°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
10°+10°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
15°+15°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
30°+30°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
60°+60°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
75°+75°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 34 cm

【Table 4.2-7-b ultimate loads of tubes -- thickness 2cm / inner diameter 34cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
30°+60°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
45°+45°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
10°+10°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
15°+15°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
30°+30°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
60°+60°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
75°+75°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 34 cm

【Table 4.2-7-c ultimate loads of tubes -- thickness 2cm / inner diameter 34cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
30°+60°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
45°+45°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
10°+10°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
15°+15°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
30°+30°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
60°+60°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06
75°+75°	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06	1.02E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 34 cm

【Table 4.2-8-a ultimate loads of tubes -- thickness 2cm / inner diameter 38cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
30°+60°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
45°+45°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
10°+10°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
15°+15°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
30°+30°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
60°+60°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
75°+75°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 38 cm

【Table 4.2-8-b ultimate loads of tubes -- thickness 2cm / inner diameter 38cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
30°+60°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
45°+45°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
10°+10°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
15°+15°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
30°+30°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
60°+60°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
75°+75°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 38 cm

【Table 4.2-8-c ultimate loads of tubes -- thickness 2cm / inner diameter 38cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
30°+60°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
45°+45°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
10°+10°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
15°+15°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
30°+30°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
60°+60°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06
75°+75°	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06	1.13E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 38 cm

【Table 4.2-9-a ultimate loads of tubes -- thickness 2cm / inner diameter 42cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
30°+60°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
45°+45°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
10°+10°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
15°+15°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
30°+30°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
60°+60°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
75°+75°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 42 cm

【Table 4.2-9-b ultimate loads of tubes -- thickness 2cm / inner diameter 42cm】

	$Long_{2\text{-}7}$	$Long_{2\text{-}8}$	$Long_{2\text{-}9}$	$Long_{2\text{-}10}$	$Long_{2\text{-}11}$	$Long_{2\text{-}12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
30°+60°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
45°+45°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
10°+10°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
15°+15°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
30°+30°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
60°+60°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
75°+75°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 42 cm

【Table 4.2-9-c ultimate loads of tubes -- thickness 2cm / inner diameter 42cm】

	$Long_{2\text{-}13}$	$Long_{2\text{-}14}$	$Long_{2\text{-}15}$	$Long_{2\text{-}16}$	$Long_{2\text{-}17}$	$Long_{2\text{-}18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
30°+60°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
45°+45°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
10°+10°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
15°+15°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
30°+30°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
60°+60°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06
75°+75°	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06	1.24E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 42 cm

【Table 4.2-10-a ultimate loads of tubes -- thickness 2cm / inner diameter 46cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
30°+60°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
45°+45°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
10°+10°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
15°+15°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
30°+30°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
60°+60°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
75°+75°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 46 cm

【Table 4.2-10-b ultimate loads of tubes -- thickness 2cm / inner diameter 46cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
30°+60°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
45°+45°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
10°+10°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
15°+15°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
30°+30°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
60°+60°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
75°+75°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 46 cm

【Table 4.2-10-c ultimate loads of tubes -- thickness 2cm / inner diameter 46cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
30°+60°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
45°+45°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
10°+10°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
15°+15°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
30°+30°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
60°+60°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06
75°+75°	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06	1.36E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 46 cm

【Table 4.2-11-a ultimate loads of tubes -- thickness 2cm / inner diameter 50cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
30°+60°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
45°+45°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
10°+10°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
15°+15°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
30°+30°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
60°+60°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
75°+75°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 50 cm

【Table 4.2-11-b ultimate loads of tubes -- thickness 2cm / inner diameter 50cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
30°+60°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
45°+45°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
10°+10°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
15°+15°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
30°+30°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
60°+60°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
75°+75°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 50 cm

【Table 4.2-11-c ultimate loads of tubes -- thickness 2cm / inner diameter 50cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
30°+60°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
45°+45°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
10°+10°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
15°+15°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
30°+30°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
60°+60°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06
75°+75°	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06	1.47E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 50 cm

【Table 4.2-12-a ultimate loads of tubes -- thickness 2cm / inner diameter 54cm】

	$Long_{2-0}$	$Long_{2-1}$	$Long_{2-2}$	$Long_{2-3}$	$Long_{2-4}$	$Long_{2-5}$	$Long_{2-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
30°+60°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
45°+45°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
10°+10°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
15°+15°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
30°+30°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
60°+60°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
75°+75°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 54 cm

【Table 4.2-12-b ultimate loads of tubes -- thickness 2cm / inner diameter 54cm】

	$Long_{2-7}$	$Long_{2-8}$	$Long_{2-9}$	$Long_{2-10}$	$Long_{2-11}$	$Long_{2-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
30°+60°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
45°+45°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
10°+10°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
15°+15°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
30°+30°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
60°+60°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
75°+75°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 54 cm

【Table 4.2-12-c ultimate loads of tubes -- thickness 2cm / inner diameter 54cm】

	$Long_{2-13}$	$Long_{2-14}$	$Long_{2-15}$	$Long_{2-16}$	$Long_{2-17}$	$Long_{2-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
30°+60°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
45°+45°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
10°+10°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
15°+15°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
30°+30°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
60°+60°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06
75°+75°	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06	1.58E+06

unit: Newton (N)
thickness: 2 cm
inner diameter: 54 cm

【Table 4.2-13-a ultimate loads of tubes -- thickness 3cm / inner diameter 10cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	5.51E+05	5.51E+05	4.80E+05	4.12E+05	3.57E+05	3.12E+05	2.76E+05
30°+60°	5.51E+05	5.51E+05	4.79E+05	4.11E+05	3.56E+05	3.11E+05	2.74E+05
45°+45°	5.51E+05	5.51E+05	4.78E+05	4.10E+05	3.55E+05	3.11E+05	2.74E+05
10°+10°	5.51E+05	5.51E+05	4.86E+05	4.17E+05	3.62E+05	3.16E+05	2.79E+05
15°+15°	5.51E+05	5.51E+05	4.86E+05	4.17E+05	3.61E+05	3.16E+05	2.79E+05
30°+30°	5.51E+05	5.51E+05	4.82E+05	4.14E+05	3.58E+05	3.13E+05	2.76E+05
60°+60°	5.51E+05	5.51E+05	4.75E+05	4.07E+05	3.53E+05	3.09E+05	2.72E+05
75°+75°	5.51E+05	5.51E+05	4.74E+05	4.06E+05	3.52E+05	3.08E+05	2.72E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 10 cm

【Table 4.2-13-b ultimate loads of tubes -- thickness 3cm / inner diameter 10cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	2.45E+05	2.19E+05	1.97E+05	1.78E+05	1.62E+05	1.48E+05
30°+60°	2.44E+05	2.18E+05	1.96E+05	1.77E+05	1.61E+05	1.47E+05
45°+45°	2.43E+05	2.17E+05	1.96E+05	1.77E+05	1.61E+05	1.46E+05
10°+10°	2.48E+05	2.22E+05	1.99E+05	1.80E+05	1.64E+05	1.49E+05
15°+15°	2.48E+05	2.21E+05	1.99E+05	1.80E+05	1.63E+05	1.49E+05
30°+30°	2.46E+05	2.20E+05	1.97E+05	1.78E+05	1.62E+05	1.48E+05
60°+60°	2.42E+05	2.16E+05	1.94E+05	1.76E+05	1.60E+05	1.46E+05
75°+75°	2.41E+05	2.16E+05	1.94E+05	1.75E+05	1.59E+05	1.45E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 10 cm

【Table 4.2-13-c ultimate loads of tubes -- thickness 3cm / inner diameter 10cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.35E+05	1.24E+05	1.15E+05	1.06E+05	9.84E+04	9.16E+04
30°+60°	1.34E+05	1.24E+05	1.14E+05	1.05E+05	9.79E+04	9.10E+04
45°+45°	1.34E+05	1.23E+05	1.14E+05	1.05E+05	9.77E+04	9.09E+04
10°+10°	1.37E+05	1.26E+05	1.16E+05	1.07E+05	9.97E+04	9.28E+04
15°+15°	1.37E+05	1.26E+05	1.16E+05	1.07E+05	9.95E+04	9.26E+04
30°+30°	1.35E+05	1.25E+05	1.15E+05	1.06E+05	9.86E+04	9.18E+04
60°+60°	1.33E+05	1.23E+05	1.13E+05	1.05E+05	9.71E+04	9.03E+04
75°+75°	1.33E+05	1.22E+05	1.13E+05	1.04E+05	9.69E+04	9.02E+04

unit: Newton (N)
thickness: 3 cm
inner diameter: 10 cm

【Table 4.2-14-a ultimate loads of tubes -- thickness 3cm / inner diameter 14cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.71E+05	5.93E+05
30°+60°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.69E+05	5.91E+05
45°+45°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.68E+05	5.90E+05
10°+10°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.79E+05	6.01E+05
15°+15°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.78E+05	6.00E+05
30°+30°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.74E+05	5.95E+05
60°+60°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.64E+05	5.87E+05
75°+75°	7.21E+05	7.21E+05	7.21E+05	7.21E+05	7.21E+05	6.62E+05	5.85E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 14 cm

【Table 4.2-14-b ultimate loads of tubes -- thickness 3cm / inner diameter 14cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	5.28E+05	4.73E+05	4.26E+05	3.85E+05	3.50E+05	3.20E+05
30°+60°	5.26E+05	4.71E+05	4.24E+05	3.84E+05	3.49E+05	3.19E+05
45°+45°	5.25E+05	4.70E+05	4.23E+05	3.83E+05	3.48E+05	3.18E+05
10°+10°	5.35E+05	4.79E+05	4.31E+05	3.90E+05	3.55E+05	3.24E+05
15°+15°	5.34E+05	4.78E+05	4.30E+05	3.90E+05	3.54E+05	3.24E+05
30°+30°	5.30E+05	4.74E+05	4.27E+05	3.87E+05	3.52E+05	3.21E+05
60°+60°	5.22E+05	4.67E+05	4.21E+05	3.81E+05	3.46E+05	3.16E+05
75°+75°	5.20E+05	4.66E+05	4.20E+05	3.80E+05	3.45E+05	3.15E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 14 cm

【Table 4.2-14-c ultimate loads of tubes -- thickness 3cm / inner diameter 14cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	2.93E+05	2.70E+05	2.49E+05	2.31E+05	2.14E+05	1.99E+05
30°+60°	2.92E+05	2.69E+05	2.48E+05	2.29E+05	2.13E+05	1.98E+05
45°+45°	2.91E+05	2.68E+05	2.47E+05	2.29E+05	2.13E+05	1.98E+05
10°+10°	2.97E+05	2.73E+05	2.52E+05	2.34E+05	2.17E+05	2.02E+05
15°+15°	2.97E+05	2.73E+05	2.52E+05	2.33E+05	2.16E+05	2.02E+05
30°+30°	2.94E+05	2.71E+05	2.50E+05	2.31E+05	2.15E+05	2.00E+05
60°+60°	2.90E+05	2.67E+05	2.46E+05	2.28E+05	2.11E+05	1.97E+05
75°+75°	2.89E+05	2.66E+05	2.45E+05	2.27E+05	2.11E+05	1.96E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 14 cm

【Table 4.2-15-a ultimate loads of tubes -- thickness 3cm / inner diameter 18cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05
30°+60°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05
45°+45°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05
10°+10°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05
15°+15°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05
30°+30°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05
60°+60°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05
75°+75°	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05	8.90E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 18 cm

【Table 4.2-15-b ultimate loads of tubes -- thickness 3cm / inner diameter 18cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	8.90E+05	8.67E+05	7.82E+05	7.09E+05	6.45E+05	5.90E+05
30°+60°	8.90E+05	8.65E+05	7.80E+05	7.07E+05	6.43E+05	5.88E+05
45°+45°	8.90E+05	8.64E+05	7.79E+05	7.06E+05	6.42E+05	5.87E+05
10°+10°	8.90E+05	8.78E+05	7.92E+05	7.18E+05	6.54E+05	5.98E+05
15°+15°	8.90E+05	8.77E+05	7.91E+05	7.17E+05	6.53E+05	5.97E+05
30°+30°	8.90E+05	8.71E+05	7.86E+05	7.12E+05	6.48E+05	5.92E+05
60°+60°	8.90E+05	8.58E+05	7.74E+05	7.01E+05	6.38E+05	5.83E+05
75°+75°	8.90E+05	8.55E+05	7.71E+05	6.99E+05	6.36E+05	5.82E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 18 cm

【Table 4.2-15-c ultimate loads of tubes -- thickness 3cm / inner diameter 18cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	5.41E+05	4.99E+05	4.60E+05	4.27E+05	3.96E+05	3.69E+05
30°+60°	5.39E+05	4.96E+05	4.59E+05	4.25E+05	3.94E+05	3.67E+05
45°+45°	5.38E+05	4.96E+05	4.58E+05	4.24E+05	3.94E+05	3.67E+05
10°+10°	5.48E+05	5.05E+05	4.67E+05	4.32E+05	4.01E+05	3.74E+05
15°+15°	5.47E+05	5.04E+05	4.66E+05	4.31E+05	4.01E+05	3.73E+05
30°+30°	5.43E+05	5.00E+05	4.62E+05	4.28E+05	3.97E+05	3.70E+05
60°+60°	5.35E+05	4.93E+05	4.55E+05	4.21E+05	3.92E+05	3.65E+05
75°+75°	5.34E+05	4.91E+05	4.54E+05	4.20E+05	3.91E+05	3.64E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 18 cm

【Table 4.2-16-a ultimate loads of tubes -- thickness 3cm / inner diameter 22cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06
30°+60°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06
45°+45°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06
10°+10°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06
15°+15°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06
30°+30°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06
60°+60°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06
75°+75°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 22 cm

【Table 4.2-16-b ultimate loads of tubes -- thickness 3cm / inner diameter 22cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	9.76E+05
30°+60°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	9.73E+05
45°+45°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	9.72E+05
10°+10°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	9.89E+05
15°+15°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	9.87E+05
30°+30°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	9.81E+05
60°+60°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.06E+06	9.66E+05
75°+75°	1.06E+06	1.06E+06	1.06E+06	1.06E+06	1.05E+06	9.63E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 22 cm

【Table 4.2-16-c ultimate loads of tubes -- thickness 3cm / inner diameter 22cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	8.96E+05	8.26E+05	7.64E+05	7.08E+05	6.58E+05	6.14E+05
30°+60°	8.94E+05	8.24E+05	7.61E+05	7.06E+05	6.56E+05	6.11E+05
45°+45°	8.93E+05	8.23E+05	7.60E+05	7.05E+05	6.55E+05	6.10E+05
10°+10°	9.08E+05	8.37E+05	7.74E+05	7.18E+05	6.67E+05	6.22E+05
15°+15°	9.07E+05	8.36E+05	7.73E+05	7.16E+05	6.66E+05	6.21E+05
30°+30°	9.01E+05	8.30E+05	7.67E+05	7.11E+05	6.61E+05	6.16E+05
60°+60°	8.87E+05	8.18E+05	7.56E+05	7.00E+05	6.51E+05	6.07E+05
75°+75°	8.84E+05	8.15E+05	7.53E+05	6.98E+05	6.49E+05	6.05E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 22 cm

【Table 4.2-17-a ultimate loads of tubes -- thickness 3cm / inner diameter 26cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
30°+60°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
45°+45°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
10°+10°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
15°+15°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
30°+30°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
60°+60°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
75°+75°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 26 cm

【Table 4.2-17-b ultimate loads of tubes -- thickness 3cm / inner diameter 26cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
30°+60°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
45°+45°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
10°+10°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
15°+15°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
30°+30°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
60°+60°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06
75°+75°	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06	1.23E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 26 cm

【Table 4.2-17-c ultimate loads of tubes -- thickness 3cm / inner diameter 26cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.23E+06	1.23E+06	1.17E+06	1.09E+06	1.01E+06	9.45E+05
30°+60°	1.23E+06	1.23E+06	1.17E+06	1.09E+06	1.01E+06	9.42E+05
45°+45°	1.23E+06	1.23E+06	1.17E+06	1.08E+06	1.01E+06	9.40E+05
10°+10°	1.23E+06	1.23E+06	1.19E+06	1.10E+06	1.03E+06	9.57E+05
15°+15°	1.23E+06	1.23E+06	1.19E+06	1.10E+06	1.02E+06	9.55E+05
30°+30°	1.23E+06	1.23E+06	1.18E+06	1.09E+06	1.02E+06	9.49E+05
60°+60°	1.23E+06	1.23E+06	1.16E+06	1.08E+06	1.00E+06	9.35E+05
75°+75°	1.23E+06	1.23E+06	1.16E+06	1.07E+06	9.99E+05	9.32E+05

unit: Newton (N)
thickness: 3 cm
inner diameter: 26 cm

【Table 4.2-18-a ultimate loads of tubes -- thickness 3cm / inner diameter 30cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
30°+60°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
45°+45°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
10°+10°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
15°+15°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
30°+30°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
60°+60°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
75°+75°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 30 cm

【Table 4.2-18-b ultimate loads of tubes -- thickness 3cm / inner diameter 30cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
30°+60°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
45°+45°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
10°+10°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
15°+15°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
30°+30°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
60°+60°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06
75°+75°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 30 cm

【Table 4.2-18-c ultimate loads of tubes -- thickness 3cm / inner diameter 30cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.36E+06
30°+60°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.37E+06
45°+45°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.37E+06
10°+10°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.37E+06
15°+15°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.39E+06
30°+30°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.39E+06
60°+60°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.38E+06
75°+75°	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.40E+06	1.36E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 30 cm

【Table 4.2-19-a ultimate loads of tubes -- thickness 3cm / inner diameter 34cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
30°+60°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
45°+45°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
10°+10°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
15°+15°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
30°+30°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
60°+60°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
75°+75°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 34 cm

【Table 4.2-19-b ultimate loads of tubes -- thickness 3cm / inner diameter 34cm】

	$Long_{3\text{-}7}$	$Long_{3\text{-}7}$	$Long_{3\text{-}9}$	$Long_{3\text{-}10}$	$Long_{3\text{-}11}$	$Long_{3\text{-}12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
30°+60°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
45°+45°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
10°+10°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
15°+15°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
30°+30°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
60°+60°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
75°+75°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 34 cm

【Table 4.2-19-c ultimate loads of tubes -- thickness 3cm / inner diameter 34cm】

	$Long_{3\text{-}13}$	$Long_{3\text{-}14}$	$Long_{3\text{-}15}$	$Long_{3\text{-}16}$	$Long_{3\text{-}17}$	$Long_{3\text{-}18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
30°+60°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
45°+45°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
10°+10°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
15°+15°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
30°+30°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
60°+60°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06
75°+75°	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06	1.57E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 34 cm

【Table 4.2-20-a ultimate loads of tubes -- thickness 3cm / inner diameter 38cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
30°+60°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
45°+45°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
10°+10°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
15°+15°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
30°+30°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
60°+60°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
75°+75°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 38 cm

【Table 4.2-20-b ultimate loads of tubes -- thickness 3cm / inner diameter 38cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
30°+60°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
45°+45°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
10°+10°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
15°+15°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
30°+30°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
60°+60°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
75°+75°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 38 cm

【Table 4.2-20-c ultimate loads of tubes -- thickness 3cm / inner diameter 38cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
30°+60°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
45°+45°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
10°+10°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
15°+15°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
30°+30°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
60°+60°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06
75°+75°	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06	1.74E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 38 cm

【Table 4.2-21-a ultimate loads of tubes -- thickness 3cm / inner diameter 42cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
30°+60°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
45°+45°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
10°+10°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
15°+15°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
30°+30°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
60°+60°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
75°+75°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 42 cm

【Table 4.2-21-b ultimate loads of tubes -- thickness 3cm / inner diameter 42cm】

	$Long_{3\text{-}7}$	$Long_{3\text{-}7}$	$Long_{3\text{-}9}$	$Long_{3\text{-}10}$	$Long_{3\text{-}11}$	$Long_{3\text{-}12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
30°+60°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
45°+45°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
10°+10°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
15°+15°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
30°+30°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
60°+60°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
75°+75°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 42 cm

【Table 4.2-21-c ultimate loads of tubes -- thickness 3cm / inner diameter 42cm】

	$Long_{3\text{-}13}$	$Long_{3\text{-}14}$	$Long_{3\text{-}15}$	$Long_{3\text{-}16}$	$Long_{3\text{-}17}$	$Long_{3\text{-}18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
30°+60°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
45°+45°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
10°+10°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
15°+15°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
30°+30°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
60°+60°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06
75°+75°	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06	1.91E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 42 cm

【Table 4.2-22-a ultimate loads of tubes -- thickness 3cm / inner diameter 46cm】

	$Long_{3\text{-}0}$	$Long_{3\text{-}1}$	$Long_{3\text{-}2}$	$Long_{3\text{-}3}$	$Long_{3\text{-}4}$	$Long_{3\text{-}5}$	$Long_{3\text{-}6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
30°+60°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
45°+45°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
10°+10°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
15°+15°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
30°+30°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
60°+60°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
75°+75°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 46 cm

【Table 4.2-22-b ultimate loads of tubes -- thickness 3cm / inner diameter 46cm】

	$Long_{3\text{-}7}$	$Long_{3\text{-}7}$	$Long_{3\text{-}9}$	$Long_{3\text{-}10}$	$Long_{3\text{-}11}$	$Long_{3\text{-}12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
30°+60°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
45°+45°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
10°+10°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
15°+15°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
30°+30°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
60°+60°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
75°+75°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 46 cm

【Table 4.2-22-c ultimate loads of tubes -- thickness 3cm / inner diameter 46cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
30°+60°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
45°+45°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
10°+10°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
15°+15°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
30°+30°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
60°+60°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06
75°+75°	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06	2.08E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 46 cm

【Table 4.2-23-a ultimate loads of tubes -- thickness 3cm / inner diameter 50cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
30°+60°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
45°+45°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
10°+10°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
15°+15°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
30°+30°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
60°+60°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
75°+75°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 50 cm

【Table 4.2-23-b ultimate loads of tubes -- thickness 3cm / inner diameter 50cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
30°+60°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
45°+45°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
10°+10°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
15°+15°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
30°+30°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
60°+60°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
75°+75°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 50 cm

【Table 4.2-23-c ultimate loads of tubes -- thickness 3cm / inner diameter 50cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
30°+60°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
45°+45°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
10°+10°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
15°+15°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
30°+30°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
60°+60°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06
75°+75°	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06	2.25E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 50 cm

【Table 4.2-24-a ultimate loads of tubes -- thickness 3cm / inner diameter 54cm】

	$Long_{3-0}$	$Long_{3-1}$	$Long_{3-2}$	$Long_{3-3}$	$Long_{3-4}$	$Long_{3-5}$	$Long_{3-6}$
length	2.50	2.75	3.00	3.25	3.50	3.75	4.00
0°+90°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
30°+60°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
45°+45°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
10°+10°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
15°+15°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
30°+30°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
60°+60°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
75°+75°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 54 cm

【Table 4.2-24-b ultimate loads of tubes -- thickness 3cm / inner diameter 54cm】

	$Long_{3-7}$	$Long_{3-7}$	$Long_{3-9}$	$Long_{3-10}$	$Long_{3-11}$	$Long_{3-12}$
length	4.25	4.50	4.75	5.00	5.25	5.50
0°+90°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
30°+60°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
45°+45°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
10°+10°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
15°+15°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
30°+30°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
60°+60°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
75°+75°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 54 cm

【Table 4.2-24-c ultimate loads of tubes -- thickness 3cm / inner diameter 54cm】

	$Long_{3-13}$	$Long_{3-14}$	$Long_{3-15}$	$Long_{3-16}$	$Long_{3-17}$	$Long_{3-18}$
length	5.75	6.00	6.25	6.50	6.75	7.00
0°+90°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
30°+60°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
45°+45°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
10°+10°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
15°+15°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
30°+30°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
60°+60°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06
75°+75°	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06	2.42E+06

unit: Newton (N)
thickness: 3 cm
inner diameter: 54 cm

4.3 Advisory Tables and Case Studies

Advisory table is a facile and simplified access for designers or engineers to adopt composite wooden tubes in practices. The philosophy and concept for the advisory table is depicted in figure 4.3-1.

four geometrical data of tubes, which are inner diameter, thickness of walls, scheme of fiber and the length of tubes. Therefore, a series of advisory table are figured out as tables 4.3-1 ~ 4.3-6.

【Table 4.3-1 advisory table 1】

Load	30 kN	40 kN	50 kN	60 kN	60 kN	70 kN	70 kN
Inner Diameter	10cm	10cm	10cm	10cm	10cm	10cm	10cm
Thickness	2.0cm	2.0cm	2.0cm	2.0cm	3.0cm	3.0cm	2.0cm
Filament	all kinds	all kinds	all kinds	all kinds	all kinds	all kinds	all kinds
Length	all kinds	all kinds	all kinds	L≤5.0M	all kinds	L≤6.5M	all kinds
Failure Mode	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling
Instruction							

【Table 4.3-2 advisory table 2】

Load	80 kN	90 kN	90 kN	100 kN	100 kN	100 kN
Inner Diameter	10cm	10cm	14cm	14cm	10cm	14cm
Thickness	3.0cm	3.0cm	2.0cm	2.0cm	2.0cm	2.0cm
Filament	all kinds	A ≤30°	all kinds	A ≤15°	all kinds	all kinds
Length	L≤6.0M	L≤5.75M	L≤6.25M	L≤6.0M	L≤3.75M	L≤5.75M
Failure Mode	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling
Instruction						

【Table 4.3-3　advisory table 3】

Load	200kN	200 kN	300 kN	300 kN	400 kN	400 kN	400 kN
Inner Diameter	18cm	10cm	18cm	22cm	14cm	26cm	22cm
Thickness	2.0cm	3.0cm	2.0cm	2.0cm	3.0cm	2.0cm	3.0cm
Filament	all kinds	all kinds	A ≤30°	A ≤30°	A ≤10°	all kinds	all kinds
Length	L≤5.75M	L≤3.75M	L≤4.75M	L≤6.25M	L≤4.0M	L≤6.75M	all kinds
Failure Mode	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling
Instruction							

【Table 4.3-4　advisory table 4】

Load	500 kN	500 kN	500 kN	600 kN	600 kN	600 kN
Inner Diameter	26cm	22cm	18cm	22cm	30cm	30cm
Thickness	2.0cm	3.0cm	3.0cm	3.0cm	2.0cm	2.0cm
Filament	all kinds	all kinds	all kinds	A ≤30°	A ≤30°	all kinds
Length	L≤6.0M	L≤6.25M	L≤4.75M	L≤5.75M	L≤6.75M	L≤6.5M
Failure Mode	Eular buckling	Eular buckling	Eular buckling	Eular buckling	Eular buckling	compression
Instruction						

【Table 4.3-5 advisory table 5】

Load	700 kN	700 kN	800 kN	800 kN	900 kN	900 kN
Inner Diameter	22cm	26cm	26cm	42cm	30cm	30cm
Thickness	3.0cm	3.0cm	3.0cm	2.0cm	2.0cm	2.0cm
Filament	all kinds	all kinds	all kinds	all kinds	all kinds	all kinds
Length	L≤5.25M	L≤6.5M	L≤6.0M	all kinds	all kinds	all kinds
Failure Mode	compression	Eular buckling	compression	compression	compression	Eular buckling
Instruction						

【Table 4.3-6 advisory table 6】

Load	1,000 kN	1,000 kN	1,500 kN
Inner Diameter	34cm	54	54cm
Thickness	3.0cm	2.0cm	3.0cm
Filament	all kinds	all kinds	all kinds
Length	all kinds	all kinds	all kinds
Failure Mode	compression	compression	compression
Instruction			

4.4 Self-weight of Various Constructions

According to the assessment foundation instructed in Ch 3.4, the appraisal results of various materials, including steel, RC, sawn wood and wooden tubes, are illustrated in figure 4.4-1 ~ figure 4.4-12.

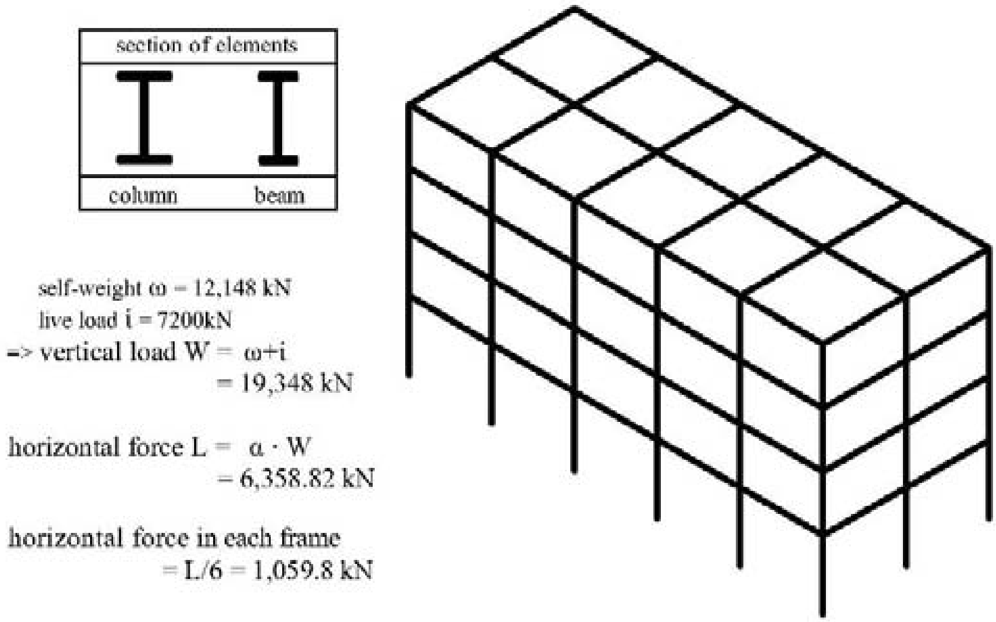


Figure 4.4-1 loading scheme of the construction model made of steel

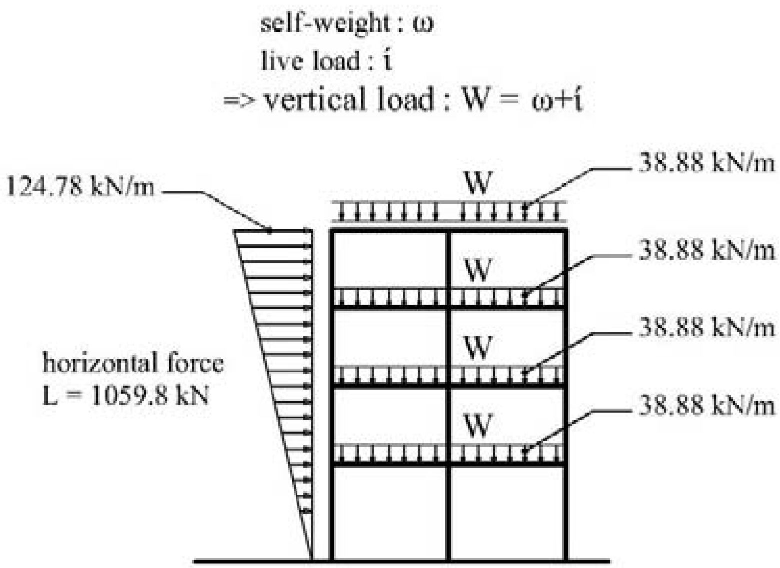


Figure 4.4-2 loading scheme of one single frame in steel model

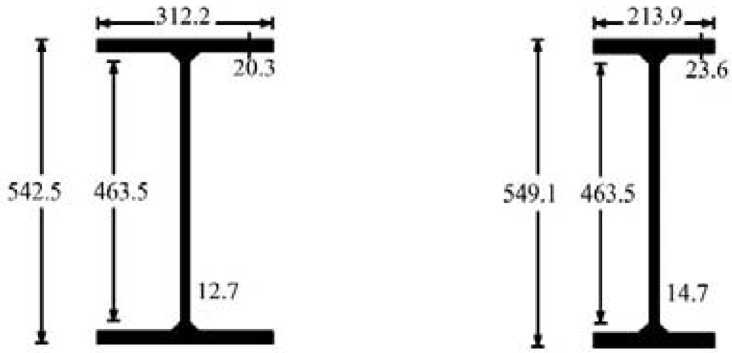


Figure 4.4-3 cross-section of columns and beams for steel model, in mini meter

In figure 4.4-3, the cross-section in left hand side is the column while that in right hand side is the beam.

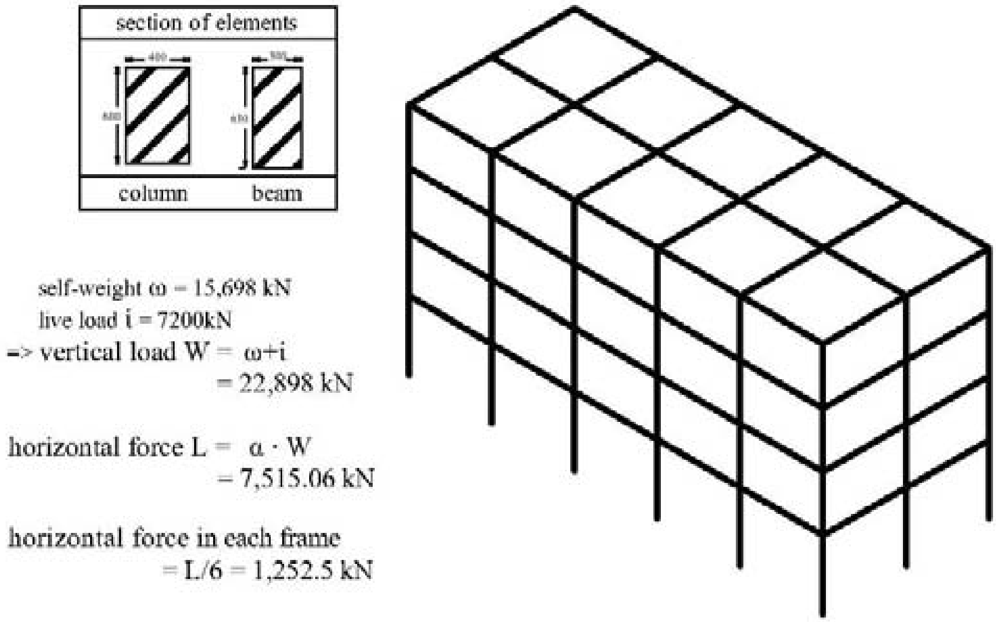


Figure 4.4-4 loading scheme of the construction model made of RC

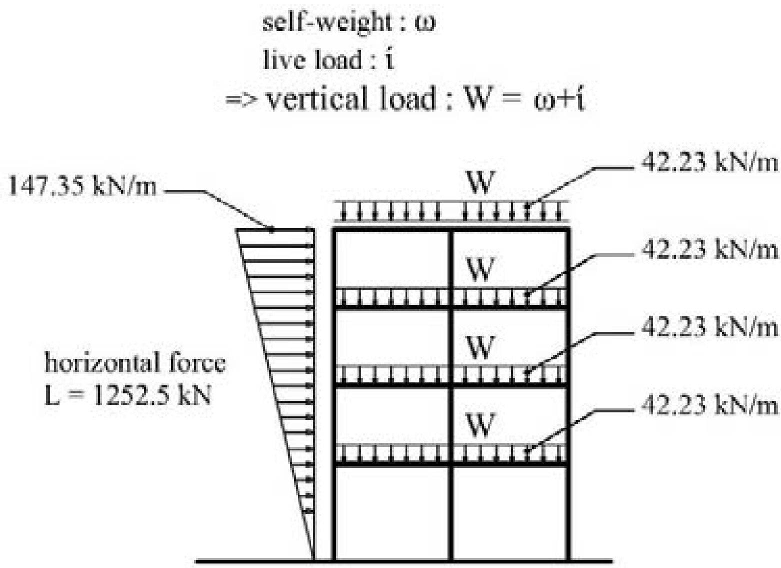


Figure 4.4-5 loading scheme of one single frame in RC model

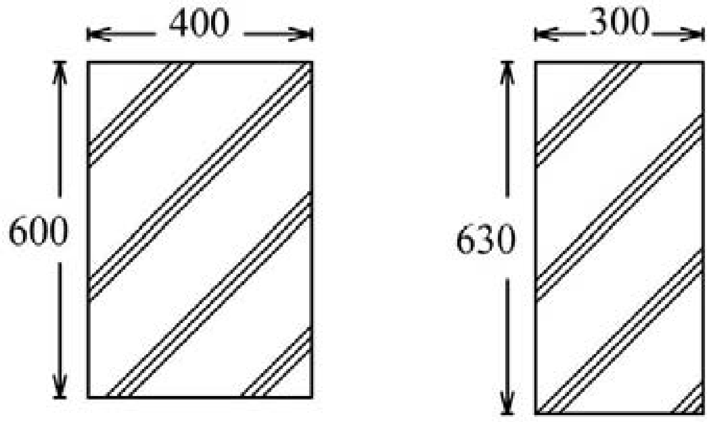


Figure 4.4-6 cross-section of columns and beams for RC model, in mini meter

In figure 4.4-6, the cross-section in left hand side is the column while that in right hand side is the beam.

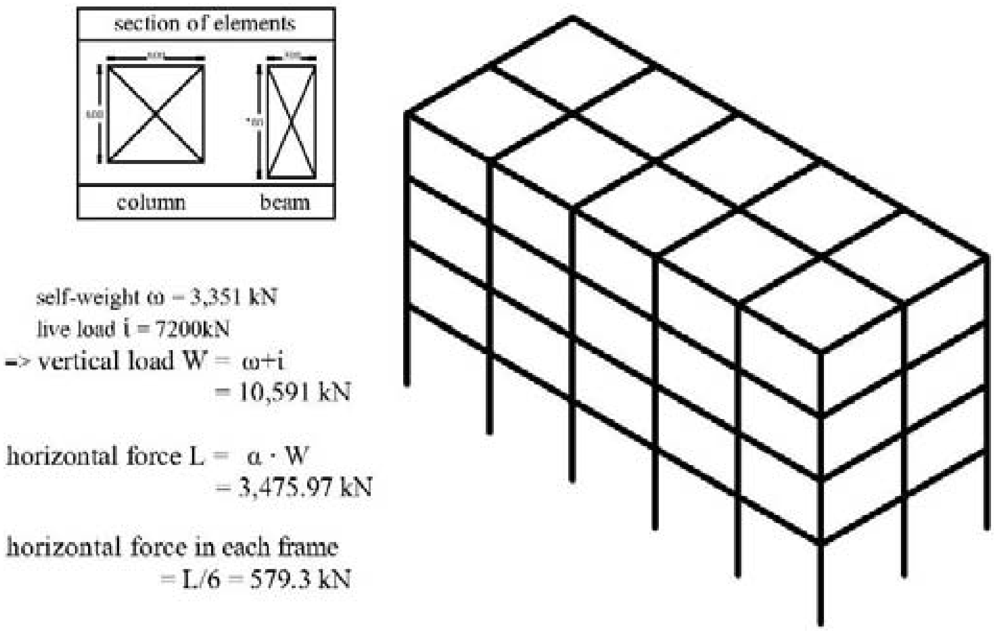


Figure 4.4-7 loading scheme of the construction model made of sawn wood

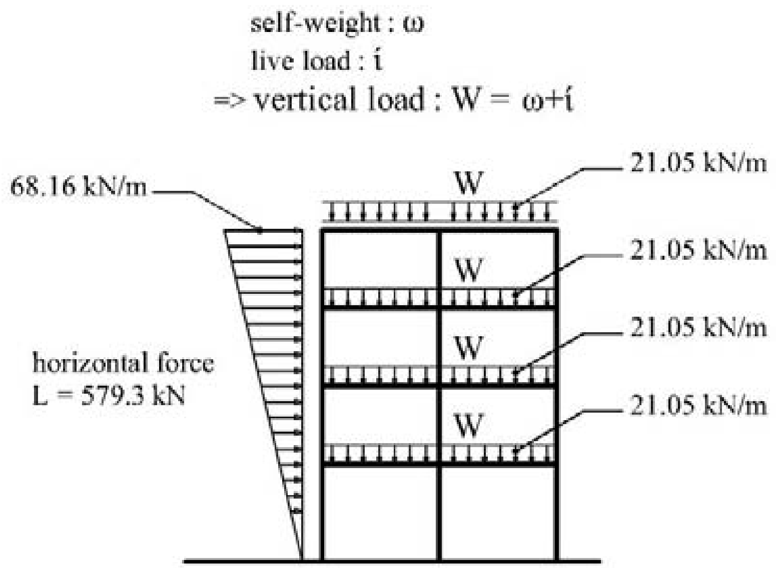


Figure 4.4-8 loading scheme of one single frame in sawn wood model

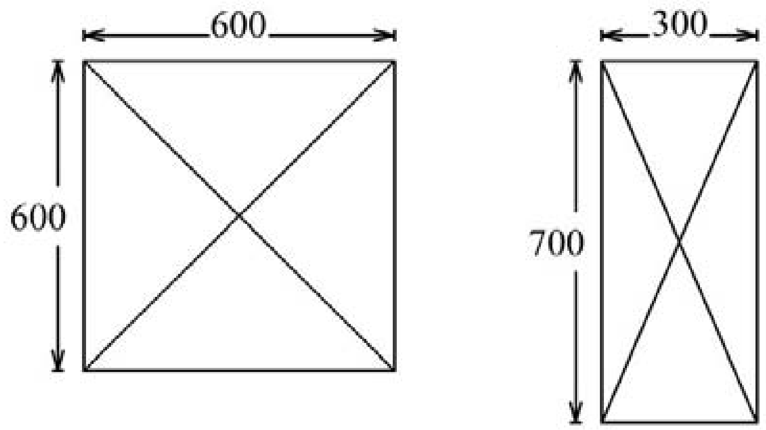


Figure 4.4-9 cross-section of columns and beams for sawn wood model, in mini meter

In figure 4.4-9, the cross-section in left hand side is the column while that in right hand side is the beam.

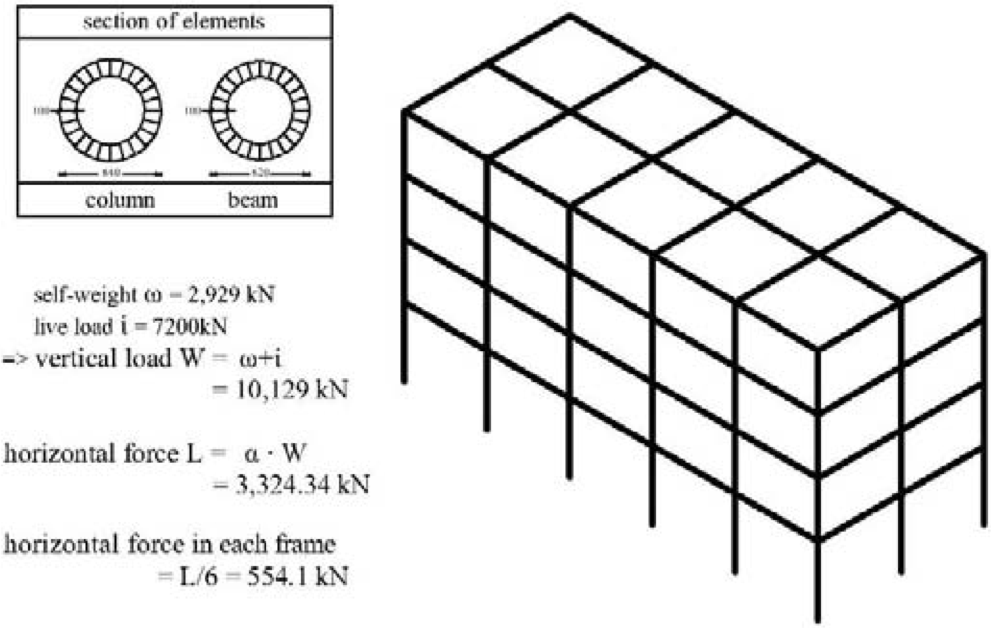


Figure 4.4-10 loading scheme of the construction model made of wooden tube

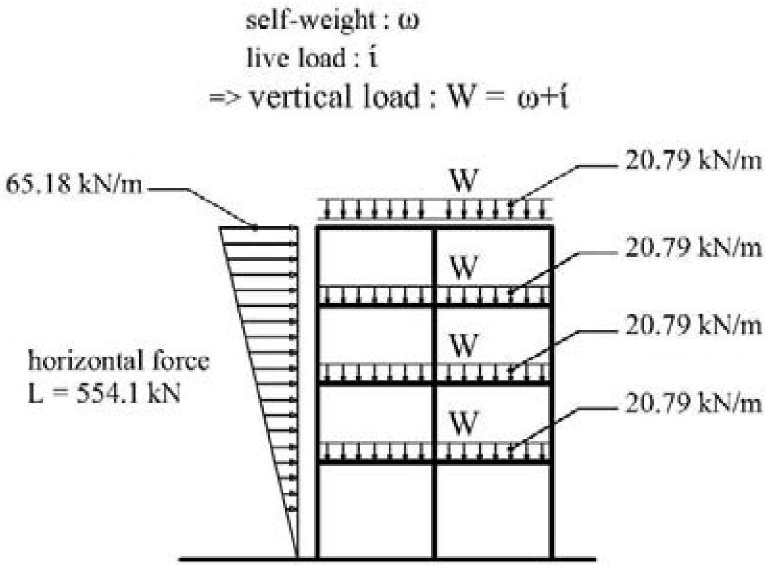


Figure 4.4-11 loading scheme of one single frame in wooden tube model

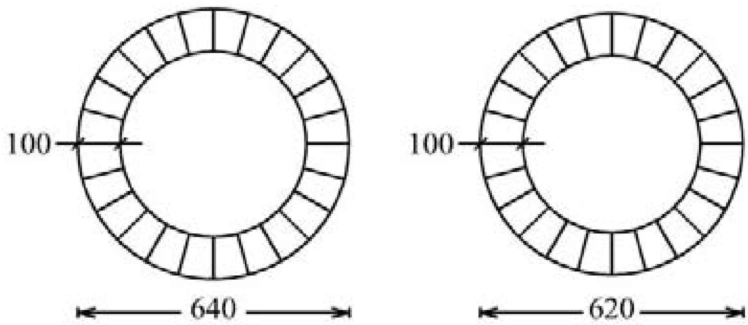


Figure 4.4-12 cross-section of columns and beams for wooden tube model, in mini meter

In figure 4.4-12, the cross-section in left hand side is the column while that in right hand side is the beam.

Table 4.4-1 shows the self-weight of each construction. Depending on this comparison result, the self-weight of the building built by sawn wood is lighter than steel and RC constructions as expected. The building composed of wooden tube is further lighter than sawn wood one. This proves that the wooden tube consists of structural and economical efficiency compared to traditional wood-based structure. The self-weight of wooden tube model is lighter than sawn wood model by about 15%. This result indicates that a building built with wooden tubes as structural elements may consume less material and require less earthquake-resistance reinforcement than sawn wood building. Compared to traditional wooden buildings, those made of composite wooden tubes are more sustainable.

【Table 4.4-1 comparison of self-weight of each construction】

	self-weight	ratio of self-weight	density	ratio of density
Steel	12147.84 kN	4,1477	78.0 kN/m^3	15.60
RC	15697.80 kN	5.3598	25.0 kN/m^3	5.00
Sawn wood	3391.20 kN	1.1579	5.0 kN/m^3	1.00
Wooden tube	2928.78 kN	1.0000	5.0 kN/m^3	1.00

note: The self-weight of wooden tube model is lighter than sawn wood one by about 15%. Self-weight of wood-based buildings are almost 1/4 that of steel and 1/5 that of reinforced concrete.

【Table 4.4-2 comparison of all vertical loads of each construction】

	vertical load	ratio of vertical load	density	ratio of density
Steel	19347.84 kN	1,9102	78.0 kN/m^3	15.60
RC	22897.80 kN	2.2607	25.0 kN/m^3	5.00
Sawn wood	10591.20 kN	1.0457	5.0 kN/m^3	1.00
Wooden tube	10128.78 kN	1.0000	5.0 kN/m^3	1.00

note: The total vertical load, including dead load and live load, of wooden tube model is lighter than sawn wood one by about 4.5%.

Since local buckling is not a critical factor in structural evaluating, users can ignore somewhat the relative parameters about local buckling as well, like the angle of fiber. Table 4.5-1 ~ 4.5-10 prove that the material properties and the estimated critical loads of local buckling are not discrepant significantly while the thickness of wooden wall has been set. Thickness of the wall plays the most influential and decisive role in for critical load of local buckling. Therefore, the third failure mode, i.e. local buckling, is not so important and ignorable in practical engineering.

【Table 4.5-1 material properties of different composite lay-up 1】

thickness of wall = **1.0** cm
unit: MPa

	0°/0°	10°/10°	15°/15°	30°/30°	45°/45°	60°/60°	80°/80°
E_x	17,660	17,560	17,460	16,990	16,520	16,260	16,210
E_y	2,160	2,155	2,153	2,212	2,470	2,933	3, 511
G_{xy}	1,467	1,515	1,570	1,775	1,878	1,775	1,515

note:

1. The maximum E_x rises in fiber angle of 0° and the value of E_x decreases while fiber angle is increasing.
2. The maximum of E_y rises in the fiber angle of 80° while the minimum is in the angle of 15°.
3. The maximum G_{xy} rises in the fiber angle of 45° and is higher than minimum G_{xy} by 28.02%

【Table 4.5-2 critical local buckling load of various composite lay-up 1】

thickness of wall = **1.0** cm
unit: N

	0°/0°	10°/10°	15°/15°	30°/30°	45°/45°	60°/60°	80°/80°
F_{local}	1.57E+06	1.59E+06	1.62E+06	1.72E+06	1.81E+06	1.83E+06	1.77E+06

note:

1. The maximum value of chessboard local buckling rises in the fiber angle of 60° while the minimum is in the angle of 0°.
2. The maximum load for chessboard local buckling is higher than minimum one by 16.3%.

【Table 4.5-3 material properties of different composite lay-up 2】

thickness of wall = **2.0** cm unit: MPa							
	0∘/0∘	10∘/10∘	15∘/15∘	30∘/30∘	45∘/45∘	60∘/60∘	80∘/80∘
E_x	17,250	17,200	17,140	16,900	16,660	16,520	16,490
E_y	1,771	1,769	1,768	1,799	1,934	2,177	2,479
G_{xy}	1,340	1,365	1,394	1,501	1,555	1,501	1,365

note:

1. The maximum E_x rises in fiber angle of 0∘ and the value of E_x decreases while fiber angle is increasing.
2. The maximum of E_y rises in the fiber angle of 80∘ while the minimum is in the angle of 15∘.
3. The maximum G_{xy} rises in the fiber angle of 45∘ and is higher than minimum G_{xy} by 16.04%

【Table 4.5-4 critical local buckling load of various composite lay-up 2】

thickness of wall = **2.0** cm unit: N							
	0∘/0∘	10∘/10∘	15∘/15∘	30∘/30∘	45∘/45∘	60∘/60∘	80∘/80∘
F_{local}	5.69E+06	5.73E+06	5.79E+06	6.01E+06	6.21E+06	6.27E+06	6.17E+06

note:

1. The maximum value of chessboard local buckling rises in the fiber angle of 60∘ while the minimum is in the angle of 0∘.
2. The maximum load for chessboard local buckling is higher than minimum one by 10.2%.

【Table 4.5-5 material properties of different composite lay-up 3】

thickness of wall = **2.7** cm unit: MPa							
	0°/0°	10°/10°	15°/15°	30°/30°	45°/45°	60°/60°	80°/80°
E_x	17,140	17,100	17,060	16,870	16,690	16,590	16,570
E_y	1,664	1,663	1,662	1,685	1,786	1,969	2,195
G_{xy}	1,305	1,324	1,345	1,426	1,466	1,426	1,324

note:

1. The maximum E_x rises in fiber angle of 0° and the value of E_x decreases while fiber angle is increasing.
2. The maximum of E_y rises in the fiber angle of 80° while the minimum is in the angle of 15°.
3. The maximum G_{xy} rises in the fiber angle of 45° and is higher than minimum G_{xy} by 12.34%

【Table 4.5-6 critical local buckling load of various composite lay-up 3】

thickness of wall = **2.7** cm unit: N							
	0°/0°	10°/10°	15°/15°	30°/30°	45°/45°	60°/60°	80°/80°
F_{local}	1.01E+07	1.01E+07	1.02E+07	1.05E+07	1.08E+07	1.09E+07	1.08E+07

note:

1. The maximum value of chessboard local buckling rises in the fiber angle of 60° while the minimum is in the angle of 0°.
2. The maximum load for chessboard local buckling is higher than minimum one by 8.1%.

【Table 4.5-7 material properties of different composite lay-up 4】

thickness of wall = **3.0** cm unit: MPa							
	0°/0°	10°/10°	15°/15°	30°/30°	45°/45°	60°/60°	80°/80°
E_x	17,100	17,070	17,030	16,870	16,700	16,610	16,590
E_y	1,633	1,632	1,631	1,652	1,744	1,908	2,113
G_{xy}	1,295	1,312	1,331	1,404	1,441	1,404	1,312

note:

1. The maximum E_x rises in fiber angle of 0° and the value of E_x decreases while fiber angle is increasing.
2. The maximum of E_y rises in the fiber angle of 80° while the minimum is in the angle of 15°.
3. The maximum G_{xy} rises in the fiber angle of 45° and is higher than minimum G_{xy} by 11.27%

【Table 4.5-8 critical local buckling load of various composite lay-up 4】

thickness of wall = **3.0** cm unit: N							
	0°/0°	10°/10°	15°/15°	30°/30°	45°/45°	60°/60°	80°/80°
F_{local}	1.23E+07	1.24E+07	1.25E+07	1.28E+07	1.31E+07	1.32E+07	1.31E+07

note:

1. The maximum value of chessboard local buckling rises in the fiber angle of 60° while the minimum is in the angle of 0°.
2. The maximum load for chessboard local buckling is higher than minimum one by 7.3%.

【Table 4.5-9 material properties of different composite lay-up 5】

thickness of wall = **4.0** cm unit: MPa							
	0∘/0∘	10∘/10∘	15∘/15∘	30∘/30∘	45∘/45∘	60∘/60∘	80∘/80∘
E_x	17,030	17,010	16,980	16,850	16,730	16,660	16,640
E_y	1,563	1,562	1,561	1,577	1,646	1,771	1,925
G_{xy}	1,272	1,285	1,299	1,354	1,382	1,354	1,285

note:

1. The maximum E_x rises in fiber angle of 0∘ and the value of E_x decreases while fiber angle is increasing.
2. The maximum of E_y rises in the fiber angle of 80∘ while the minimum is in the angle of 15∘.
3. The maximum G_{xy} rises in the fiber angle of 45∘ and is higher than minimum G_{xy} by 8.65%

【Table 4.5-10 critical local buckling load of various composite lay-up 5】

thickness of wall = **4.0** cm unit: N							
	0∘/0∘	10∘/10∘	15∘/15∘	30∘/30∘	45∘/45∘	60∘/60∘	80∘/80∘
F_{local}	2.14E+07	2.15E+07	2.16E+07	2.21E+07	2.25E+07	2.27E+07	2.25E+07

note:

1. The maximum value of chessboard local buckling rises in the fiber angle of 60∘ while the minimum is in the angle of 0∘.
2. The maximum load for chessboard local buckling is higher than minimum one by 5.9%.

In order to find out the appropriate cross-section area and moment inertia, designers can adopt and solve the formulae shown in equation 4.5-1. Since these two factors are derived from the geometrical scheme f cross-section, the diameter and thickness are the origin for them. For plotting the equations, diameter and thickness are converted into outer and inner diameter of the wooden tubes.

$$\begin{aligned} (r_o^2 - r_i^2) * \pi &\geqq A_{min} \\ (r_o^4 - r_i^4) / 4 * \pi &\geqq I_{min} \end{aligned} \qquad (4.5\text{-}1)$$

By solving these equations and finding out the outer and inner diameter, an optimal profile of tubes comes out subsequently.

In the other hand, the required diameter and thickness can be retrieved by means of try and error. Since the engineers can write a program or calculating procedure in computer, users can attempt to key in various geometrical value until the area of cross-section and the moment inertia achieved the criteria. For example, EXCEL of Microsoft Office could be a widely available, compactable and adoptable tool to complete the task.

Chapter 5 Conclusions and Prospects

5.1 Conclusions

This research framework finally derives 5 conclusions about application of cylindrical composite wooden tubes.

Firstly, compared to the equations provided by Weaver, Michaeli's formulae are feasible for predicting the structural behavior of composite tubes. The estimated results are more conservative than those from Wearver's system. This research thus adopted Michaeli's formulae to appraise the ultimate loads and failure modes of tubes. Furthermore, Michaeli's formula is applied to evaluate tube's behavior in the sequential studies.

Secondly, cylindrical composite wooden tubes with ordinary dimension can serve well for general buildings like houses, low-rise housing and office buildings.

This research has set a series of tubes depending on the general geometry and dimension available in human environment. Such arrangement makes it possible to compare the capability and feasibility of composite tubes with traditional materials. It proves that composite tubes possess structural competency and economical efficiency since they consume less material but consist of equivalent capacity as others.

The designed group of tubes has been demonstrated that they are serviceable and adoptable. It is possible to commercialize these tubes in the future. Manufacturing the tubes by means of massive producing and pre-fabricate techniques may precipitate the broadcast of this engineered wood. Composite tubes perform as well as general materials while the scale and dimension are not extremely specialized. This superiority provides a chance to develop tubes in commercial market.

Thirdly, an advisory table for engineers to apply tubes in buildings is figured out and serves as a facile access to carry out tubes in practice.

After the design of a structure and subsequent analysis, the load which each element should afford would be plotted. With the consciousness of the design load, plus security factor, designers and engineers can select a feasible tube for specialized loading circumstances depending on the conceived advisory table. This simplified methodology makes the application and broadcast of tubes in building engineering easier and sooner.

Fourth, the building built with composite wooden tubes possesses lower self-weight compared to the building composed of traditional sawn wood. The self-weight of the former one is lower than the later one by around 15%.

Lighter self-weight refers to less material consumption. In the meanwhile, the lateral force caused by ground motion would be reduced since this force is derived from the self-weight. With this advantage, a building composed of wooden tube need less invention to reinforce or stiffen. This is an evidence of structural and economical efficiency.

Finally, an optimal profile of tubes subjected to assigned load is available. With the methodology figured out in this research framework, the geometrical scheme of tubes can be adjusted to satisfy the definition for “optimal” profile. In this methodology, cross-sectional area and moment inertia are respectively the dominant factor of the corresponding failure mode. By means of adjusting these two factors and acquiring the proper geometry, the optimized profile for certain load arises.

Designing tubes in optimized profile can restrict the consumption of material, which lead to an economical and sustainable utilization for material. This process correspond the ultimate target of finding a sustainable and reliable material and using it in an efficient way.

5.2 Prospects and Subsequent Researches

Although the advisory table conceived in this research supplies a convenient way to adopt composite tubes in practical engineering, some aspects for this application remains unclear and need to be further refined. This advisory table takes only the axial load into account. In buildings, however, bending effect always occurs somewhat in compressive elements. Despite this research has adopted a security factor of 1.5 to ensure its reliability, it is still necessary to explore the bending behavior of tubes subjected to moment.

Connecting methodologies and techniques remain difficult and unclear for joining cylindrical tubes firmly. For broadcasting and applying tubes in buildings, this is an critical problem to solve. It is necessary to develop a reliable way to combine the tubes with each other or with other material. Researches about joints could put composite tubes in a wider range of application.

In the end, fire resistance and thermal effect are significant problems for tubes. FRP reinforcement surrounds the tube and provides restriction to the wooden tube, which causes the enhancement of stiffness and strength of the material. In fire and moisture attack, however, the fiber may be influenced negatively by heat and humidity. It is important to evaluate how far these factors may affect the behavior of the composites.

Reference

【1】Holzbulletin, 73/2004, Vier und mehr Geschosse

【2】Cheung, K. (2008): Multi-storey timber and mixed timber-RC/steel constructions in USA. *Structural Engineering International*, Vol. 18, No.2, pp. 122 ~ 125

【3】Jorrison, A. J. M., Leijten, A. J. M. (2008): Tall timber buildings in the Netherlands. *Structural Engineering International*, Vol. 18, No.2, pp. 133 ~ 136

【4】Holzbulletin, 75/2005, Gewerbe- und Industriebauten

【5】Holzbulletin, 80/2006, Büroräume

【6】Holzbulletin, 86/2008, Mehrgeschossige Wohnbauten

【7】Holzbulletin, 81/2006, Kanton Tessin

【8】Heiduschke, A., Kasal, B., Haller, P. (2008): Performance and drift levels of tall timber frame buildings under seismic and wind loads. *Structural Engineering International*, Vol. 18, No.2, pp. 186 ~ 191

【9】Ceccotti, A. (2008): New technologies for construction of medium-rise buildings in seismic regions: the XLAM case. *Structural Engineering International*, Vol. 18, No.2, pp. 156 ~ 165

【10】Li, J. (1995): Wood based composite material toward 21st century. *Wood forestry Research*, Vol.3, pp. 34~39

【11】Herzog, T., Natterer, J., Sweitzer R., Volz, M., Winter, W. (2004): Timber Construction Manuel, English Edition, Birkhäuser, Basel

【12】Haller, P. (2007): Concepts for textile reinforcement for timber structures.

Materials and Structures, 40, p.p. 107~118

【13】Yanagawa, Y., Kawai, S., Sasaki, H. (2001): Properties of glass fiber reinforced laminated veneer lumber produced with a continuous stream injection press and lamination effect. *Symposium on Utilization of Agriculture and Forestry Residues, Nanjing, China*, pp. 328~332

【14】Xiong, X., Zhang, D. (2003): Research on the property test of CFRP cloth reinforcing log. *Journal of Chuzhou Vocational & Technical College*, Vol. 2, No.3

【15】Zhang, D., Xiong, X., Zhang, P. (2002): Research on the CFRP and pre-stressed reinforcing ancient wooden construction. *Industrial Construction*.

【16】Wang, Z., He, Y., Wang, P. (2004): Application and research on FRP in the reinforcement of timber structures. *Building Technique Development*, Vol. 31, No. 3.

【17】Xie, Q., Zao, H., Xue, J., Yao, K., Sui, Y. (2008): An experimental study on the strengthening of motise-tenon joints in ancient Chinese wooden buildings. *China Civil Engineering Journal*, Vol. 41, No. 1.

【18】Li, D., Xu, Y., Zheng, G. (2002): Problems for repairing Ying-xian wooden tower and countermeasures. *Earthquake Research in Shanxi*, No. 2.

【19】Weaver, P. M. (2000): Design of laminated composite cylindrical shells under axial compression. *Composites: Part B: Engineering*, 31, p.p. 669~679

【20】Michaeli, W., Huyberchts, D., Wegener., M. (1994): Dimensionieren mit Faserverbund-kunststoffen -- Einführung und praktische Hilfen. Carl Hanser, München

【21】Roberto, L. A., Antonis, M., Thomas, C. S. (2003): Experimental characterization FRP composite wood pile structural response by bending test. *Marine Structures*, 16, pp. 257~274

【22】Li, Y-F., Xie, Y-M., Tsai, M-J. (2008): Enhancement of the flexural performance of retrofitted wood beams using CFRP composite sheets, Construction and Building Material.

【23】Tsai, S. W. (1990): Theory of Composite Design, Dayton: think composite

【24】Young, W. C. (1989): Roark’s formulas for stress and strain, McGraw-Hill, New York

【25】Anon. (1968): Thin-walled circular cylinders, NASA Report

【26】Allen, H. G., Bulsen, P. S. (1980): Background to buckling, McGraw-Hill, New York

【27】Dow, N. F., Rosen, B. W. (1966): Structural efficiency of orthotropic cylindrical shells subjected to axial compression, AIAA J, 4, pp. 481 ~ 485

【28】Weaver, P. M. (1999): Computer aided laminated selection using a graphical method, ICCM12, 5±9

【29】Pelleitier, J. L., Vel, S. S. (2006): Multi-objective optimization of fiber reinforced composite laminates for strength, stiffness and minimal mass. *Computers and Structures*, 84, pp. 2065 ~ 2080

【30】Petutschnigg, A. J., Ebner, M. (2007): Lightweight paper materials for furniture -- A design study to develop and evaluate materials and joints. *Materials and Design*, 28, pp. 408 ~ 413

【31】Weaver, P. M., Ashby, M. F. (1997): Material limits for shape efficiency. *Progress in Material Science*, Vol. 41, pp. 61 ~ 128

【32】Gutkowski, R., Brown K., Shigidi, J., Natterer, J. (2007): Laboratory tests of composite wood-concrete beams. *Construction and Building Materials*

【33】Kasal, B., Collins, M. S., Paevere, P., Foliente, G. C. (2004): Design models of light frame wood buildings under lateral loads. Journal of Structural Engineering, 130: 8, pp. 1263 ~ 1271