BEHAVIOUR OF CABLE-STAYED BRIDGE WITH CABLE LOSSES

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for the award of the
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ABSTRACT

Progressive collapse have always been a serious threat to cable-stayed bridge, and has historically caused vast demolition of man-made structure and loss of lives. It is a kind of structural failure, which caused by breakdown of a particular structural part and the incapability of the structural system to cope with the disruption of force. A chain reaction will be generated, causing the destruction of the whole bridge structure. In this research, the structural performance of a cable-stayed bridge under cable failure has been studied.

This research demonstrate the modelling and analysis of the simplified and modified Penang Second Bridge using SAP2000. This work study the performance of cable-stayed bridge with and without loaded of the static vehicle. This work was also examine the structural response of the cable-stayed bridge to the loss of cables. The progressive collapse analysis has done by removing the cables and checking their effect on the cable axial force.

ABSTRAK

Keruntuhan progresif adalah ancaman terhadap jambatan kabel. Masalah ini telah banyak memusnahkan harta benda dan meragut nyawa manusia. Keruntuhan progresif adalah disebabkan oleh kegagalan struktur. Bahagian struktur jambatan yang gagal akan menyebabkan kemusnahan sistem struktur dan keruntuhan seluruh struktur jambatan. Dalam kajian ini, reaksi struktur jambatan kabel atas kegagalan kabel telah diuji.

Kajian ini menunjukkan pemodelan dan analisis Jambatan Kedua Pulau Pinang yang dipermudahkan dan diubahsuai dengan menggunakan SAP2000. Kajian ini menguji reaksi jambatan kabel atas kemuatan kenderaan statik. Kerja-kerja ini juga akan mengkaji tindak balas struktur jambatan kabel atas kehilangan kabel. Analisis keruntuhan progresif akan dilakukan dengan mengeluarkan kabel dan memeriksa kesannya pada daya paksi kabel.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

A bridge is built to provide passage over the obstacle. It comes with a different design when encountered with a different situation. Each of them has their particular purpose and function. The cable-stayed bridge is a bridge where its cable holds the deck by connecting it directly to the towers. The cables usually come in four kind of designs, which are the harp, fan, mono and star. A semi-fan or semi-harp design is usually preferred as it is more practical especially when many cables are involved. There is also four kinds of column arrangement among the cable-stayed bridge design, which is single, double, portal and A-shaped.

Cable-stayed bridges are first found in 1595, where the designs were found in Machinae Novae, a book by Venetian inventor Fausto Veranzio (X.Niu, 2013). Many suspension bridge at early were similar to the cable-stayed. The designers are then found that cable-stayed bridge is stiffer and more economic. Construction of this type of bridge continued into the 20th century where modern concrete stayed bridges with concrete or steel decked were built (J.Niels, 1999). Today the concrete stayed bridge can be built in different varieties and types.

There is always a confusion between a suspension bridge and a cable-stayed bridge. At first glance, these two bridge are looking alike, but there is a difference between their construction and principle. In suspension bridges, there are large main cables which anchored to the ground hanging between the pylons. It bears the load of the bridge deck. The tension of the main cables is then transferred to the ground at the anchorages. The forces within the bridge are shown in Figure1.1.

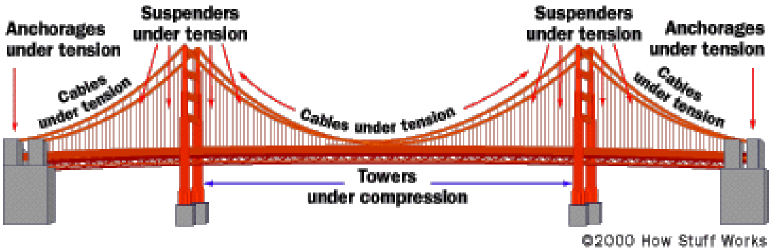

Figure 1.1 Forces within suspension bridge

(Robert Lamb, Michael Morrissey, 2000)

Cable-stayed bridges also have the towers and decks which held by cables, but the deck are connected directly to the towers through cables. For the deck near the towers, cantilevers are used to support their weight. Cable-stayed bridge requires stronger bridge deck to resist the horizontal compression loads. Figure 1.2 shows the force within the cable-stayed bridge.

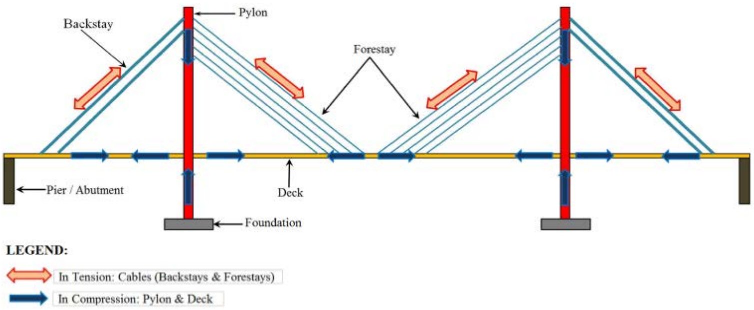

Figure 1.2 Forces within a cable-stayed bridge system

(M Khairussaleh, A Nor, 2016)

In a cable-stayed bridge, the forces are exerted on all the main parts, which are the cables, pylons and the deck. The weight of the deck is held by the cables, making it stretched and in tension. The pylons are under compression of both the weight of cables and deck. The deck is under both compression and tension as the top of the deck is stretched to tension condition while its bottom being compressed.

1.2 Problem Statement

Since cable-stayed bridge have been introduced, this type of bridge has been known for its stiff structure. However, failures are still happening, resulting in massive loss of money and materials. Some bridge failure will even cause life loss. The study of the past failure incident is essential for us to enhance the construction method and bridge design.

One of the causes of these damages is the failure in a number of elements during ultimate events such as an earthquake or severe wind. In these types of failures, earthquake or wind act as primary perturbation factors which propagate the local failure within the structure. They are natural disasters which are unavoidable Unpredictable events like terrorist attacks and vehicle collision also cause failure in some elements due to loading beyond the capacity. The failure of the bridge can be prevented with a proper design and quality control. A lot of variation has to be taken into consideration when a bridge is designed. The failure of any structural element should be measured as a possible local failure for cable stayed bridges will lead to low resistances against accidental lateral loads from vehicle impact or accidental actions. The loss of cables can lead to overloading and rupture of adjacent cables.

In a cable-stayed bridge, each cable is bearing with different loading depending on where it is installed. When failures occurred, progressive collapse tends to happen in a cable-stayed bridge. The loss of cables must be considered as a possible local failure since the cross sections of cables are usually small, and therefore provide low resistances against accidental lateral loads stemming from vehicle impact or malicious action (Buscemi, N., Marjanishvili, S.,2005).

The loss of cables can lead to overloading and rupture of adjacent cables. Furthermore, the stiffening girder is in compression and a cable loss reduces its bracing against buckling (Buscemi, N., Marjanishvili, S.,2005).

1.3 Objectives

i. To study the performance of cable-stayed bridge with fully loaded and without loading of the static vehicle using the Eurocode.
ii. To study the performance of cable-stayed bridge under cable loses.
iii. To study the progressive collapse vulnerability of a cable-stayed bridge.

1.4 Project Scopes

To achieve the project properties, SAP2000 is used on modelling the cable stayed bridge. This project will demonstrate the modelling and analysis of a cable-stayed bridge. A simplified Sultan Abdul Halim Muadzam Shah Bridge will be modelled for this study. The performance of the cable-stayed bridge over different loading combination will be tested.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

To achieve the project properties, SAP2000 is used on modelling the cable stayed bridge. This project will demonstrate the modelling and analysis of a cable-stayed bridge. A simplified Sultan Abdul Halim Muadzam Shah Bridge will be modelled for this study. The performance of the cable-stayed bridge over different loading combination will be tested.

This chapter will discuss the history of the cable-stayed bridge, the structure of the cable-stayed bridge, the arrangement of cables, the variation of the cable-stayed bridge and the progressive collapse of cable-stayed bridges and type of cables.

2.2 History of Cable-Stayed Bridge

The design of the cable-stayed bridge was first found in 1595, from a book name Machinae Novae, written by the Venetian inventor Fausto Veranzio (X.Niu, 2013). It is a timber beam which directly supported by bars in combination with suspension cable and the parallel arrangement of the ties are similar to harp shape (Svensson, 2013).

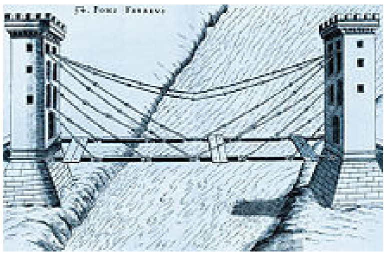

Figure 2.1 Cable-stayed bridge by the Renaissance polymath Fausto Veranzio,

from 1595/1616 (Niu.X, 2013)

The design concept of a cable-stayed bridge, which is to support the bridge deck with inclined tension members on either side of the span has been known for centuries (J.Niels, 1999). Cable-stayed bridge at early age uses natural materials such as bamboo for the beam and lianas for ties (Svensson, 2013). However, the uses of this material are not sturdy to be used as the tension member for a bridge. After wrought iron bars and steel wires with reliable tensile strength have been developed, this design concept has become one of the options in the bridge construction (J.Niels, 1999). However, the system is still not popular and accepted at that time. In the second half of the 19th century, suspension bridges with cable system were built. These bridge comprising suspension system with parabolic main cables and vertical hangers with cables radiating from pylon tops (J.Niels, 1999). Some of the most notable bridges of this type are the Dryburgh Abbey Bridge (1817), Victoria Bridge (1836), Albert Bridge (1872), and Brooklyn Bridge (1883).

Figure 2.2 Dryburgh Abbey Bridge, built in 1817. (Klaus Föhl, 2005)

Figure 2.3 Victoria Bridge, built in 1836. (Philip Halling, 2007)

Figure 2.4 Albert Bridge, built in 1872. (Inge Kanakaris-Wirtl, 2009)

Figure 2.5 Brooklyn Bridge, built in 1883. (Postdlf, 2005)

Modern cable-stayed bridge has stay cables with well-defined and tuned cable forces which transfer their load directly (Svensson, 2013). They have a span with a greater length which can only achieved by suspension bridge in the past. The Strömsund Bridge built in 1956 located in Sweden is considered as the first cable-stayed bridge with a modern design where the cables structure and load distribution had reached its finest efficiency (J.Niels, 1999). The next modern cable-stayed bridge is the Theodor Heuss Bridge located at Düsseldorf, German. At the 1960s, this bridge has become an example for other cable-stayed bridge in term of its modern structure and design (J.Niels, 1999).

Figure 2.6 Strömsund Bridge at Sweden (Lars Falkdalen, 1955)

Figure 2.7 Theodor Heuss Bridge at Düsseldorf

(Werner Huthmacher, 2008)

Early of cable-stayed bridge construction, steel was widely used as a structural material. The cables, girders, pylons and deck were constructed of steel (J.Niels, 1999). However, innovation had been made in 1962 on The General Rafael Urdaneta Bridge in Venezuela, both of its deck girder and pylons were constructed in concrete.

Figure 2.8 General Rafael Urdaneta Bridge at Venezuela

(Orlando Pozo, 2009)

In the 1970s the concrete cable-stayed bridge becomes more and more popular and can finally compete with steel bridges (J.Niels, 1999). Brotonne Bridge, the first multi-cable concrete bridge had been built across the Seine in 1977.

Figure 2.9 Brotonne bridge (Pont de Brotonne) in France

(Philip Bourret, 2006)

In 1984, Barrios de Luna Bridge in Spain was constructed. This bridge further proved that how concrete can be used in the construction of bridges. This bridge have a main span of 440m which was the longest at that time (J.Niels, 1999).

Figure 2.10 Barrios de Luna Bridge (Robert Cortright, 2005)

The record holder title has passed to the Alex Fraser Bridge which was opened in 1986. It has the main span of 465m.

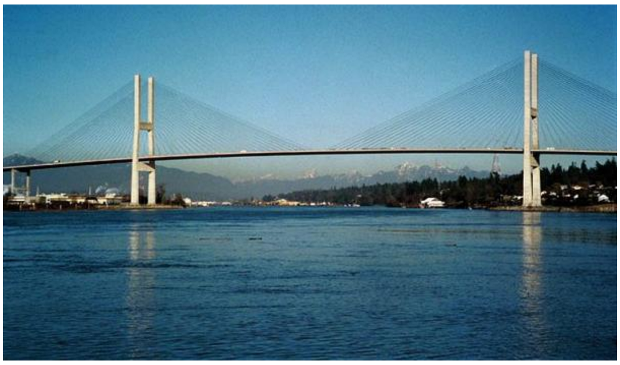

Figure 2.11 Alex Fraser Bridge (Robert Cortright, 1995)

Among the development of the cable-stayed bridge, the establishment of the multi-cable system is one of the compelling development as it simplified the erection procedure and made the cable replacement of bridge easier (J.Niels, 1999).This progress have consequently resulted in a general acceptance of this system in the other cable-stayed bridges. Despite the advantages of the multi-cable system, it actually increases the total wind load on the cable system and having a higher vulnerability to excitations.

In Japan, the first double deck cable-stayed bridge, Rokko Bridge have been constructed at 1976 (J.Niels, 1999).The concept of the double deck was then further used in the construction of twin cable-stayed bridge, such as the Hitsuishijima and Iwagurojima bridges. These bridges carry a four-lane expressway on the upper deck and a double track railway on the lower deck. The first S-curved cable-stayed bridge in the world, which is the Katsuhika Harp Bridge was also constructed by Japan in 1980.

Figure 2.12 Hitsuishijima Bridge (far) and Iwagurojima Bridge (near)

(Norito, 2006)

Figure 2.13 Katsuhika Harp Bridge (Lerk, 2006)

Figure 2.14 S Curve of Katsuhika Harp Bridge

(Dionysius M.Siringoringo, 2007)

The rapid progress can be attributed to the development of box-girders with orthotropic plate decks; the manufacturing techniques of high-strength wires that can be used for cables; the use of electronic computers in structural analysis and design; and the advances in prestressed concrete structures (Niemeyer, T. K, *et al*, 2006). The reconstruction of bridges in Europe, primarily Germany, destroyed during World War II provided bridge engineers with the opportunity to apply the modern design on the cable-stayed bridge (Niemeyer, T. K, *et al*, 2006). After years of rapid development, the popularity of cable-stayed bridge has been increased (Niemeyer, T. K, *et al*, 2006). It has now become a popular option among the bridge design. This is largely due to the appealing aesthetics; the full and efficient utilization of structural materials; the increased stiffness over suspension bridges; the efficient and fast mode of construction; and the relatively small size of the bridge elements.

2.3 Structure of Cable-Stayed Bridge

The structure of a standard cable-stayed bridge is formed by a deck with one or two pylons lifted above the piers at mid span. Extra supports are provided to the using the cables which installed diagonally to the girder.

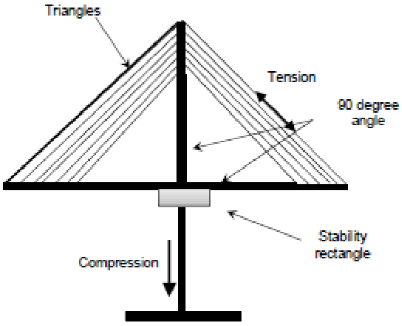

Figure 2.15 A simple illustration of the typical cable-stayed bridge (O.Zadeh, 2012).

The primary load-bearing structure of a cable-stayed bridge is formed by the pylons. As shown in Figure 2.15, starting from the deck, the compression forces are then transferred to the cables to the pylons and into the foundation. In order to minimize the height of the pylon, the static horizontal forces from dead load have to be balanced (O.Zadeh, 2012). To resist earthquakes, the centre of gravity of the bridge has to be low. The cables with a small diameter and special overhead structure give the cable-stayed bridge an exceptional architectural appearance (O.Zadeh, 2012). There are three main components in a cable-stayed bridge as shown as below.

2.3.1 Deck

The deck act as a roadway in a cable-stayed bridge. Materials such as steel, concrete and composite steel-concrete can be used to construct the deck. The material used directly affect the overall cost of the cable-stayed bridge construction. The selection of stay cables, pylons, and foundations are based on the weight of the deck (Bernard *et al.*, 1988). The composite steel-concrete deck is composed of two structural edge girders as shown in Figure 2.16. The transverse steel floor beams are adhere with the girders. Two main girders are used to support the precast reinforced concrete deck. This type of composite steel-concrete deck has more advantages as follow (Hassan *et al.*, 2012):

- Steel girders are minimized by using the precast slab
- The steel girders can be erected before applying the heavy concrete slab.
- The stay cables have more resistance against rotation anchoring to the outside steel main girders.
- The precast slab is used to minimize the redistribution of compression forces from the shrinkage of the steel girders.

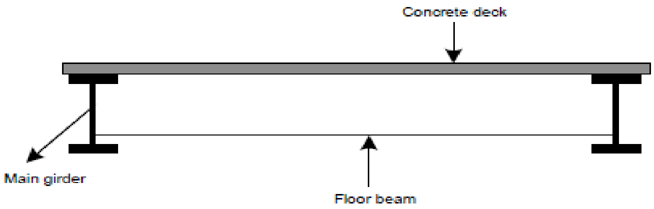

Figure 2.16 Composite Deck (O.Zadeh, 2012).

2.3.2 Pylons

Pylons of cable stayed bridges provide support to the bridge against the weight and live load. The shape of pylon used to depend on the characteristic of the bridge such as the aesthetics, length, and arrangement of cables. Type of pylon used either single, double, portal or A-shaped. There are also four arrangements for support columns: single, double, portal and A-shaped.

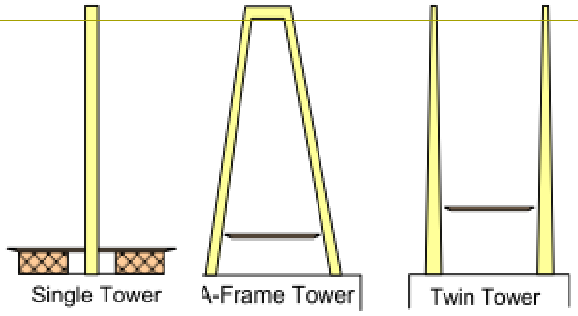

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Figure 2.17 single, double, and A-shaped pylon (N.Anwar, n.d)

- The single arrangement uses a single column for cable support, normally projecting through the center of the deck, but in some cases located on one side or the other.
- The double arrangement places pairs of columns on both sides of the deck.
- The portal is similar to the double arrangement but has a third member connecting the tops of the two columns to form a door-like shape or portal. This offers additional strength, especially against traverse loads.
- The A-shaped design is similar in concept to the portal but achieves the same goal by angling the two columns towards each other to meet at the top, eliminating the need for the third member. The inverted Y design combines the A-shaped on the bottom with the single on top.

Depending on the design, the columns may be vertical or angled or curved relative to the bridge deck.

2.3.3 Cables

Cables act as a medium to transfer the load from the deck to the pylons. The cables are always in post-tensioned and used to minimize both the lateral deflection of the pylons and the vertical deflection of the deck (O.Zadeh, 2012). The selection of cables are depend on the economical parameter, the structural and mechanical properties (O.Zadeh, 2012). Three types of cables arrangement which have been used in cable-stayed bridge are harp, fan and semi-fan.

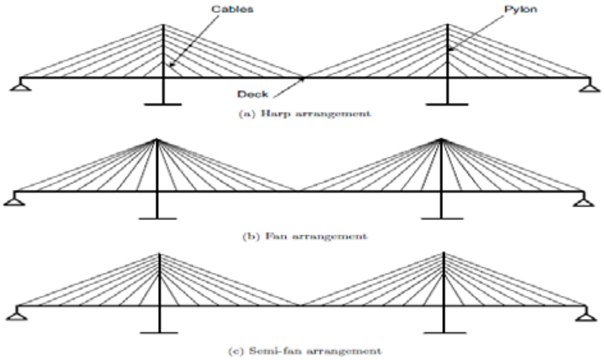


Figure 2.18 Types of Cable-Stayed Bridge (O.Zadeh, 2012).

2.4 Arrangement of Cables

There are 3 type of cables arrangement as shown as below, which is the harp arrangement, fan arrangement and semi-fan arrangement.

2.4.1 Harp arrangement

In a harp arrangement, cables are attached parallelly to the pylon on different points as shown in Figure 2.17. This kind of bridge give an attractive appearance compared to another type of bridge. However, the cables will consumed more steel in this kind or arrangement. As a results, long span bridges with harp arrangement are not economically efficient. The increased amount of compression in the deck will produce more bending moments in the pylon (O.Zadeh, 2012). Taller pylons are also required in this kind of bridge.

2.4.2 Fan arrangement

In fan arrangement, stay cables are attached to one point at top of each pylon as shown in Fig. 2.17. The cable cross section is smaller due to the relatively steep slope of the stay cables (O.Zadeh, 2012). The horizontal cable forces are lesser in compared with the harp arrangement (Bernard et al., 1988). This type of arrangement is more suitable for moderate span bridge with lesser stay cables. When the number of stay cables increased, the attachment of stay cables to anchorage become harder as the weight of anchorage is increased.

2.4.3 Semi-fan arrangement

This type of arrangement is more favourable in modern cable-stayed bridges due to its efficiency (O.Zadeh, 2012). The cables are distributed over the upper part of the pylon, which is more steeply inclined close to the pylon (Bernard et al., 1988). This kind of arrangement gives more aesthetic pleasure in compared with the fan arrangement. The world largest cable-stayed bridge (Sutong Bridge in Jiangsu, China) was designed as a semi-fan arrangement using A-shape pylons.

Fig 2.19 Sutong Bridge (Nicolas Janberg, 2009)

2.5 Variations of Cable-Stayed Bridge

A side-spar cable-stayed bridge allows the bridge to be constructed in curve shape. It has only one central tower which supported on only one side. The tower of this kind of bridge can be the offset and it is not limited to a straight bridge. The Chords Bridge in Jerusalem, is a side-spar cable stayed bridge which the bridge deck can wrap around the spar in an arc (Zandberg, Esther, 2004)

Figure 2.20 Chords Bridge in Jerusalem (Hovev, 2008)

Cantilever-spar cable-stayed bridge uses a single cantilever spar on one side of the span to support the deck. The bridge applies large overturning force to its foundation as the cable forces are not balanced by opposing cables. The cable bending is resisted by the spar. The Puente del Alamillo in Spain (1992) is one of this kind of bridge with a radical design.

Figure 2.21 Puente del Alamillo in Spain (Galván , 2011)

Multiple-span cable-stayed bridge has a complex structure as it has more than three spans. Overall the bridge is less stiff as the loads from the main spans are not anchored back near the end abutments. Alternate design such as cross-bracing and multi-legged framed towers will be used to strengthen the bridge. The General Rafael Urdaneta Bridge in Venezuela is one of the example which stiff multi-legged frame towers are adopted (Virlogeux, Michel, 2001).

Figure 2.22 General Rafael Urdaneta Bridge in Venezuela (Orlando Pozo, 2009)

The extradosed bridge has longer gaps between each cable supported section. The cables connected to the bridge are lower and further from the pylons, making the deck stronger and stiffer. The Twinkle-Kisogawa in Japan is an example of extradosed bridge.

Figure 2.23 Twinkle-Kisogawa in Japan (Tawashi, 2006)

Cable-stayed cradle-system bridge has a cradle system which carries the strands within the stays between bridge decks. The cables can be removed as there is no anchorages in the towers. The Penobscot Narrows Bridge and the Veterans' Glass City Skyway are the first two bridge with this kind of design.

Figure 2.24 The Penobscot Narrows Bridge (Gladys L, 2009.)

Figure 2.25 Veterans' Glass City Skyway (Brady J, 2009)

2.6 Progressive Collapse in Cable-Stayed Bridge

Progressive collapse has always been a serious threat to the cable-stayed bridge, and has historically caused the vast demolition of man-made structure and loss of lives. It is a kind of structural failure, which is generated by a sectional structure failure and eventually causing a chain reaction resulting in disruption of a major part of the structural system. The discharge of internal energy caused by the instantaneous loss of a structural part will violate the initial load equilibrium and eventually caused progressive collapse. In addition, the structure will vibrate until either a new equilibrium position is found or it collapses (Das.R, 2016).

The mechanism of collapse for bridges is not identical to buildings. Bridges are primarily horizontally aligned structures with one main axis of extension (Das.R, 2016). The loss of cables should be measured as a possible local failure since the cross sections of cables are usually small, and therefore provide low resistances against accidental lateral loads stemming from vehicle impact or accidental actions. Cable losing will cause increase the bearing load of adjacent cables and finally direct into cable failure and rupture. The loss of cable will also cause defection on the stiffening girder on its compressive nature resulting failure in the bracing of girder against buckling.

2.6.1 Reason Causing Progressive Collapse

The reason of the progressive collapse in the cable-stayed bridge can be generally classified into three point (Liu *et al*, 2011):

a. inaccurate design or faulty construction methods,
b. the spontaneous incidents such as an earthquake or heavy collisions
c. the deterioration of structure performances including corrosion and creep effect

2.6.2 Progression of Progressive Collapse

There are two failure progression (Das.R, 2016).:

a. Partial-failure type.

   A fractional part of load-bearing components in bridge having defection, resulting in the adjustment of the structural stiffness and internal forces, thus causing the progressive collapse. For example, in 2001, the Xiaonanmen Bridge collapsed because of stress corrosion of some ruptured hangers after being struck by an overweight truck (Das.R, 2016).

b. Bearing-failure type

   The decrease in the internal force distribution and statically indeterminacy degree. For example, the collapse of Guangdong Jiujiang Bridge. Four continuous spans of the bridge were facing failure because of the collision between a fish and one of its piers.

2.6.3 Analysis on the Model of Cable-Stayed Bridge on Progressive Collapse

There are four modified analytical procedures on analyzing of the model of cable-stayed bridge on progressive collapse, the linear static, nonlinear static, linear dynamic and nonlinear dynamic (Fatollahzadeh.A *et al*, 2016). The static analysis is relatively conservative when compared with the nonlinear dynamic analysis. The nonlinear dynamic analysis needs to be conducted with the initial state given by nonlinear static procedure for a better result on the tracing of progressive collapse.

In the studies of 2D cable-stayed bridge model, it was found that if the cable tensions of faulty cable were small, the progressive collapse will not happen (Cai *et al,* 2012). The breakdown of a single cable only bring a little alteration on the load bearing system and so no rupture of cables occurred. However, when the number of fail cables increased, the adjacent cable will start to yield while the bridge continues to be stable. When the live load was increased by two factors or more, the adjacent cables of the lost cables will be deformed and progressive collapse will begin (Cai et al, 2012). Cables near the pylon will also experience less yield tension and lower nodal vertical displacement escalation.

2.7 Type of Cable

The basic element of cables is the single wire. Seven-wire strand which used in tendons for pre-stressed concrete is the simplest strand in cable supported bridges. Normally, the cable strand has a nominal diameter of 15mm and is made from seven 5mm wires as shown in Figure 2.26.

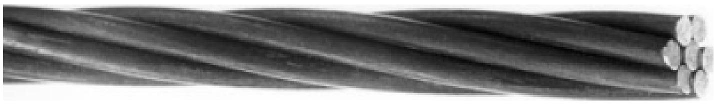


Figure 2.26 Seven-wire strand (Narotama, 2012).

The tensile strength of a common seven-wire strands is between 1770 and 1860 MPa (Narotama, 2012). A single straight core wire lies between the layer of six wires, all share same pitch and direction of the helix. Normally, the seven-wire strand comprises of the modulus of elasticity which is 6–8% lower than for the wires themselves, i.e. a typical modulus of elasticity of E ¼ 190 GPa (Narotama, 2012).

There is 7 basic type of cables, which are the Helical bridge strands (spiral strands), Locked-coil strands, Parallel-wire strands for suspension bridge main cables, New PWS stay cables, Bar stay cables, Multi-strand stay cables, parallel-strand stay cables as shown as figure 2.27 to 2.32 respectively.

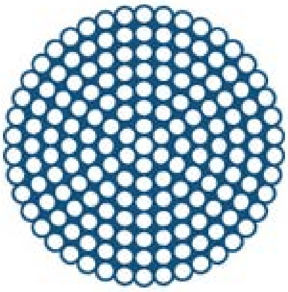


Figure 2.27 Cross-section of spiral strand

(Brindon International Ltd, 2013).

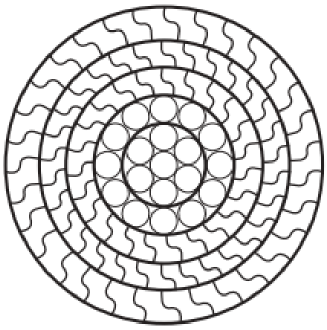


Figure 2.28 Cross-section of locked-coil strand

(Narotama University 2012).

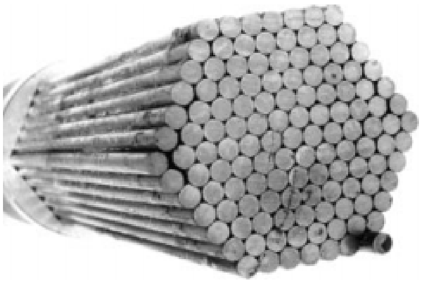


Figure 2.29 cross-section of Parallel-wire strands for

Suspension bridge main cables

(Narotama University , 2012).

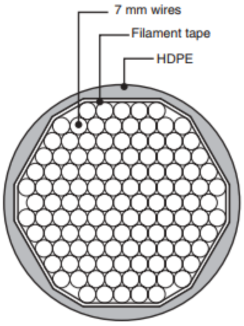


Figure 2.30 Cross-section of new PWS cable

(Narotama University , 2012).

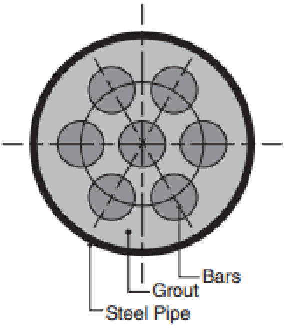


Figure 2.31 Cross-section of bar stay cables

(Narotama University , 2012).

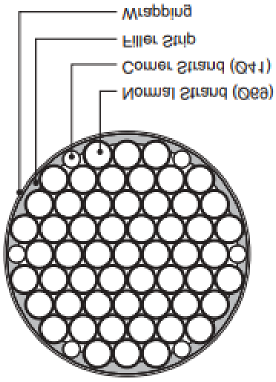


Figure 2.32 Cross-section of multi strand stay cables

(Narotama University , 2012).

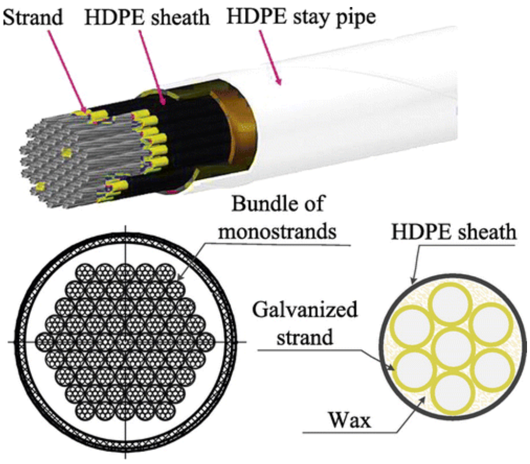


Figure 2.33 Cross-section of parallel-strand stay cables

(W. Ronghui et al , 2013)

‘

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will explain the flow chart of the project, sample model of the cable-stayed bridge, the modelling of a cable-stayed bridge, and the load condition.

3.2 Flow Chart of Project

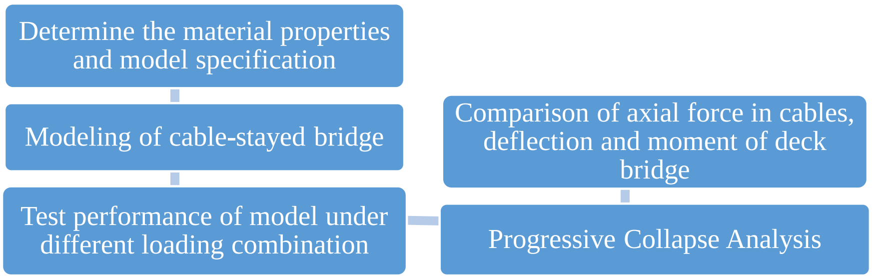


Figure 3.1 Flow Chart of Project

3.3 Sample model of Cable-Stayed Bridge

The Sultan Abdul Halim Muadzam Shah Bridge, which also known as The Penang Second Bridge is used as a sample for the model of the cable-stayed bridge in this project. It is the longest bridge structure in South East Asia. It serve as a dual carriageway toll bridge in Penang, connecting Batu Kawan on mainland Peninsular Malaysia with Batu Maung on Penang Island.

Due to geological reasons, The Second Penang Bridge is designed based on the double "S". It is a cable-stayed bridge with harp system. It has a total length of

24km and is build 6m above the water. The bridge length over water is 16.9km and its length of the expressway is 7.1km. The main navigation span of the bridge is 475m.

Figure 3.2 The Sultan Abdul Halim Muadzam Shah Bridge

(Marufish, 2008)

3.4 The Modelling of Cable-Stayed Bridge

The modelling of cable stayed bridge has been done by using the commercially available computer program SAP2000 (CSI, 2008, SAP2000 Version 20, Computer and Structure. Inc). SAP2000 is the easiest most productive solution for structural analysis and design needs. It can analyse simple 2D frames as well as the complex 3D structures. It is the most suitable finite element tool for modelling and progressive collapse analysis of cable-stayed bridges.

A harp shape cable stay bridge model will be created based on main navigation span of the simplified Sultan Abdul Halim Muadzam Shah Bridge. It has a main span of 240m, with two 117.5m side spans. There are 4 pairs of pylons for the main navigation span. Two pair of main pylons with height of 97m at the mid span and the other two pair of 38m at back span. The deck width is 35.6m.

The simplified model bridge deck is made of reinforced concrete U girder with concrete strength of 4000 psi (27.58 N/mm^2). 144 cables with the diameter of 200mm are used in this bridge. The stay cables consists of the Parallel Strand System (PSS) made up of parallel individually polyethylene coated wire strands, placed inside an external polyethylene stay pipe. There are 17 strands of 21mm with the modulus of elasticity of 1.99E+05N/mm^2 within the cable.

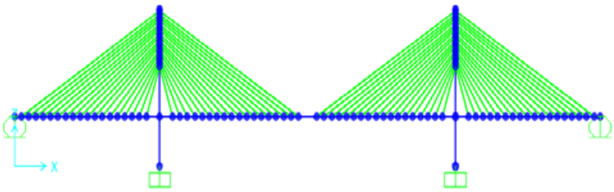


Figure 3.3 Model of Cable-Stayed Bridge in 2D

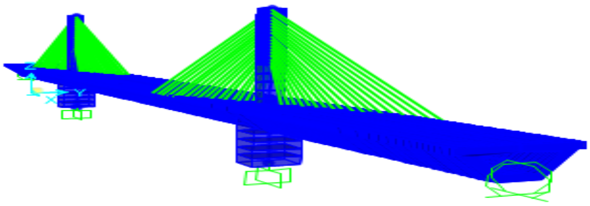


Figure 3.4 Model of Cable-Stayed Bridge in 3D

3.5 The Load Condition

In this study, the cable stayed bridge is evaluated under the effect of dead load (Self weight), cable load (strain) and live load (traffic). The following combination are used:

- Load combination=1.0DL+1.0CL
- Load combination=1.0DL+1.0CL+1.0LL at left side span
- Load combination=1.0DL+1.0CL+1.0LL at mid span

3.6 The Progressive Collapse

Using the model created, the progressive collapse analysis is then done by removing the critical cables. The analysis was done by checking their effects on the axial cable forces.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter shows the data of the bridge model analysis by using SAP2000. The bridge model is evaluated under different load combination. The effect of cable losses on the bridge model will also be shown. Figure 4.1 and 4.2 shows the model cable-stayed bridge in 2D and 3D.

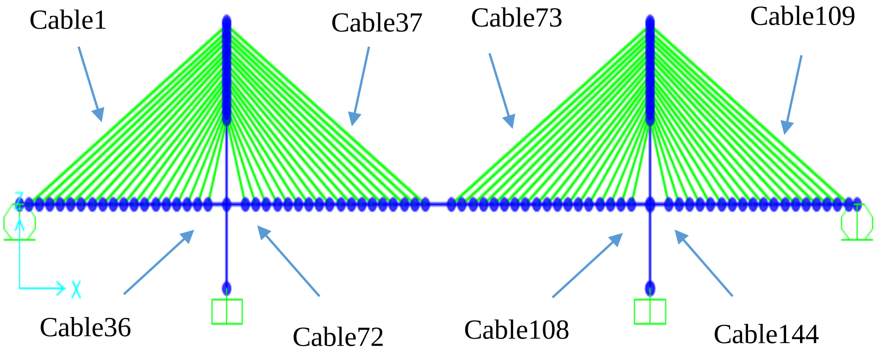


Figure 4.1 Model of Cable-Stayed Bridge in 2D

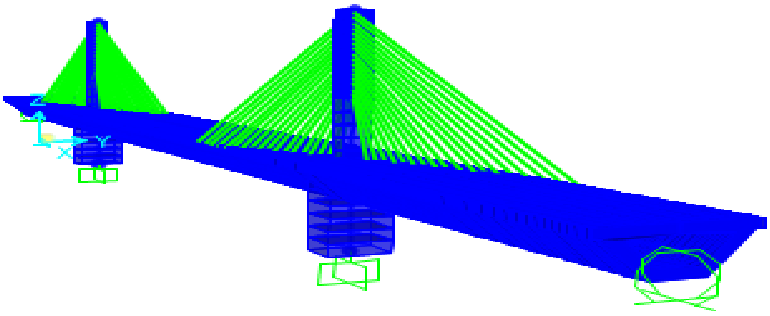


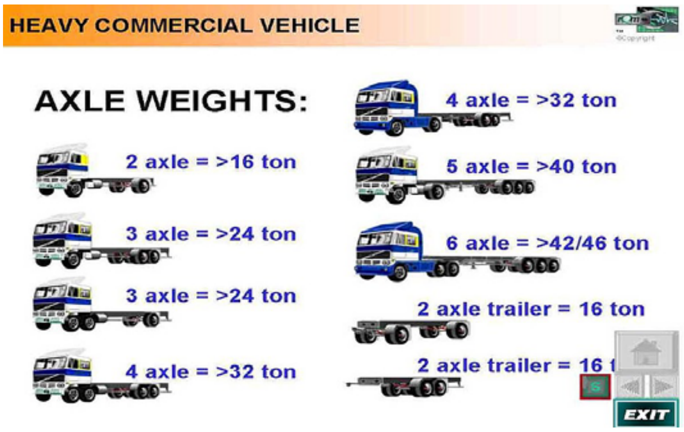
Figure 4.2 Model of Cable-Stayed Bridge in 3D

4.2 Cable-Stayed Bridge under Vehicle Load

The cable-stayed bridge model is tested under the loading of static vehicle. The performance of the model bridge with and without loaded will be recorded and compared.

4.2.1 Vehicle Load

In this study, the weight of 25 3axle trucks (5978kN) was applied on the model bridge. Figure 4.3 shows the categories of heavy vehicles.



HEAVY COMMERCIAL VEHICLE

AXLE WEIGHTS:

2 axle = >16 ton
3 axle = >24 ton
3 axle = >24 ton
4 axle = >32 ton
4 axle = >32 ton
5 axle = >40 ton
6 axle = >42/46 ton
2 axle trailer = 16 ton
2 axle trailer = 16 t

Figure 4.3 Heavy Commercial Vehicle Categories (Vehicle Construction Part 4 Trucks)

The weight of trucks is uniformly distributed throughout the bridge span as a live load of 50kN/m. The bridge model are tested under 3 load condition:

- No vehicle load
- Vehicle load at side span
- Vehicle load at mid span

Figures 4.4 to 4.7 shows the bridge model with live load and their deformation.

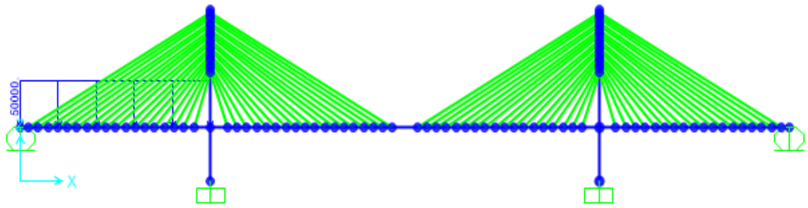


Figure 4.4 50kN/m Live Load at the Left Side Span of Bridge

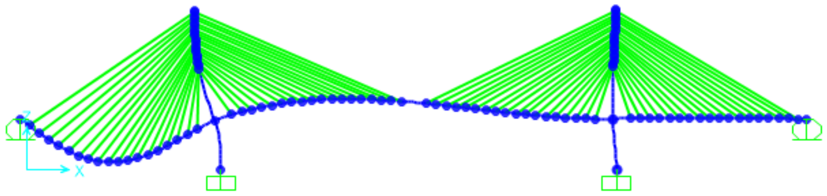


Figure 4.5 Deformation of Bridge under 50kN/m Live Load at the Side Span of Bridge

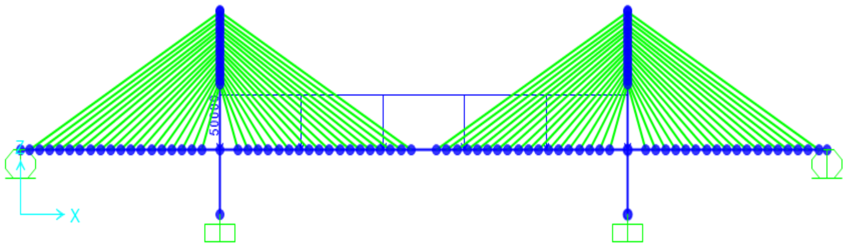


Figure 4.6 50kN/m at the Mid Span of Bridge

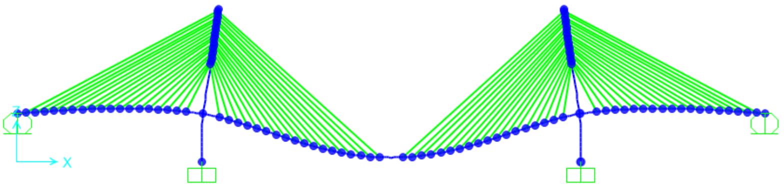


Table 4.7 Deformation of Bridge under 50kN/m Live Load at the Mid Span of Bridge

4.2.2 Cable Stress of Bridge under Vehicle Load

The cable stress of the model bridge before and after the vehicle load applied were compared. Table 4.1 to 4.3 shows the cable stresses of bridge model under different load condition.

Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)
1	2928.16	37	2926.74	19	2927.80	55	2927.64
2	2924.16	38	2921.56	20	2922.81	56	2923.37
3	2920.10	39	2916.48	21	2917.94	57	2919.02
4	2916.03	40	2911.55	22	2913.23	58	2914.62
5	2512.01	41	2506.84	23	2508.76	59	2510.26
6	2507.79	42	2502.09	24	2504.28	60	2505.68
7	2503.45	43	2497.41	25	2499.88	61	2500.95
8	2498.90	44	2492.71	26	2495.47	62	2496.01
9	2494.10	45	2487.96	27	2491.02	63	2490.80
10	1889.10	46	2483.09	28	1886.61	64	2485.25
11	1883.26	47	1878.09	29	1881.59	65	1879.35
12	1876.52	48	1872.32	30	1875.90	66	1872.43
13	1868.61	49	1865.66	31	1869.28	67	1864.42
14	1859.17	50	1857.72	32	1861.33	68	1854.94
15	1447.98	51	1448.21	33	1451.75	69	1443.80
16	1434.48	52	1436.37	34	1439.77	70	1430.45
17	1418.91	53	1422.06	35	1425.27	71	1415.14
18	1402.84	54	1406.11	36	1409.09	72	1399.45

Table 4.1 Cable Stresses without Vehicle Load

Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)
1	2928.50	37	2926.83	19	2927.61	55	2927.71
2	2924.42	38	2921.65	20	2922.62	56	2923.43

3	2920.28	39	2916.57	21	2917.76	57	2919.08
4	2916.11	40	2911.64	22	2913.06	58	2914.68
5	2512.00	41	2506.93	23	2508.60	59	2510.33
6	2507.69	42	2502.18	24	2504.13	60	2505.74
7	2503.25	43	2497.49	25	2499.74	61	2501.02
8	2498.62	44	2492.79	26	2495.34	62	2496.07
9	2493.72	45	2488.03	27	2490.90	63	2490.86
10	1888.65	46	2483.16	28	1886.51	64	2485.32
11	1882.74	47	1878.15	29	1881.50	65	1879.41
12	1875.94	48	1872.36	30	1875.82	66	1872.49
13	1867.99	49	1865.70	31	1869.23	67	1864.48
14	1858.53	50	1857.75	32	1861.29	68	1855.00
15	1447.36	51	1448.23	33	1451.74	69	1443.86
16	1433.90	52	1436.37	34	1439.79	70	1430.50
17	1418.44	53	1422.05	35	1425.31	71	1415.18
18	1402.52	54	1406.09	36	1409.14	72	1399.48

Table 4.2 Cable Stresses with 50kN/m Load at Left Side Span

Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)	Cable	Stress (N/mm^2)
1	2930.51	37	2928.10	19	2928.87	55	2929.72
2	2926.40	38	2923.07	20	2924.04	56	2925.41
3	2922.22	39	2918.14	21	2919.32	57	2921.02
4	2918.01	40	2913.33	22	2914.75	58	2916.58
5	2513.85	41	2508.74	23	2510.41	59	2512.17
6	2509.48	42	2504.09	24	2506.04	60	2507.53
7	2504.99	43	2499.48	25	2501.73	61	2502.75
8	2500.28	44	2494.84	26	2497.39	62	2497.74
9	2495.31	45	2490.12	27	2492.99	63	2492.45
10	1890.15	46	2485.25	28	1888.60	64	2486.82
11	1884.15	47	1880.21	29	1883.56	65	1880.82
12	1877.23	48	1874.36	30	1877.82	66	1873.79
13	1869.16	49	1867.58	31	1871.11	67	1865.65
14	1859.55	50	1859. 46	32	1863.00	68	1856.02
15	1448.21	51	1449.70	33	1453.22	69	1444.71
16	1434.56	52	1437.54	34	1440.96	70	1431.16
17	1418.87	53	1422.85	35	1426.11	71	1415.62
18	1402.72	54	1406.48	36	1409.53	72	1399.68

Table 4.3 Cable Stresses with 50kN/m Load at Mid Span

Table 4.3 shows that the cable stresses of the cable-stayed bridge increase when there is vehicle load. From both the load application, the side span of the bridge (cable 1-18, cable 55-72) have higher stress differences. For example, when the vehicle load is applied at the mid span, the stress differences between 1 to 18 and 55 to 72 are higher than the stress differences between 19 to 36 and 55 to 72 as shown as Table 4.4. The cables at side span are more affected from the load translation. They tend to suffer more severe stress from the vehicles and more fragile in progressive collapse.

Cable	Stress Differences (N/mm^2)
1 to 18	1527.79
19 to 36	1519.35
37 to 54	1521.62
55 to 72	1530.04

Table 4.4 Cable Stress Differences between Cables

4.3 Cable Losses in Cable-Stayed Bridge

The left part of the bridge (cable 1 – 36) was used to show the effect of cable loss to the bridge. One cable was removed at a time. The decrease of stresses in the pylon and bridge deck, and the cable axial forces of the rest of cables were recorded and compared.

4.3.1 Axial Forces in Cable under Cable Losses

Table 4.5 to 4.8 and Figure 4.8 shows the cable axial force when the cables are being removed one at a time.

Cable	Axial Force (kN)									
1	91785.30	Removed	99258.43	98530.78	97241.37	96017.09	95549.69	94781.45	94298.02	93983.41
2	91644.80	99576.24	Removed	98268.86	97048.26	95872.88	95438.33	94692.10	94232.51	93931.15
3	91501.30	99105.61	98537.14	Removed	96846.50	95724.87	95326.43	94604.40	94170.82	93884.06
4	82448.70	89002.70	88562.61	88140.87	Removed	86253.74	85930.29	85303.13	84937.59	84693.51
5	70976.90	77211.78	76841.93	76488.30	75638.99	Removed	74486.15	73887.05	73550.07	73322.77
6	70839.40	76747.90	76445.44	76157.10	75386.39	74582.75	Removed	73804.25	73499.34	73291.48
7	63451.70	68457.55	68243.87	68041.03	67418.59	66756.46	66606.69	Removed	65916.30	65750.34
8	63318.90	68025.03	67866.33	67716.71	67162.01	66558.41	66447.40	66036.74	Removed	65714.58
9	63179.60	67584.24	67477.60	67378.34	66889.66	66343.73	66269.40	65897.03	65753.65	Removed
10	47146.40	46266.63	46215.20	46168.91	45790.19	45353.77	45318.24	45019.70	44923.65	44872.44
11	47002.70	45848.70	45838.02	45831.10	45507.73	45120.89	45114.05	44848.53	44782.58	44756.40
12	40305.10	45408.80	45435.61	45464.86	45194.86	44856.63	44876.15	44643.06	44605.31	44602.29
13	37313.20	39807.86	39861.40	39916.02	39722.23	39464.85	39503.08	39324.85	39314.44	39330.37
14	37125.70	39355.22	39434.27	39513.42	39362.87	39146.95	39203.10	39052.72	39062.94	39095.12
15	28886.80	30814.78	30913.57	31011.62	30901.66	30726.48	30796.50	30673.64	30701.36	30746.63
16	25147.90	26590.09	26686.99	26782.69	26718.56	26599.67	26668.32	26584.24	26620.08	26667.43
17	24899.60	26039.66	26135.83	26230.53	26194.13	26109.18	26177.40	26116.75	26158.27	26207.36
18	24658.30	25456.20	25535.93	25614.34	25598.09	25544.60	25601.45	25563.03	25601.69	25644.02
19	92158.60	90933.26	91030.21	91122.09	91273.30	91345.57	91412.82	91513.80	89956.73	90249.31
20	92010.10	84932.95	85498.85	86040.80	87141.63	88227.34	88639.29	89323.52	89771.26	90049.35
21	91664.10	84733.27	85375.57	86005.19	87101.72	88130.58	88507.91	89164.16	89585.90	89848.31
22	82787.80	76849.05	77292.82	77717.39	78586.80	79459.34	79765.72	80330.43	80685.57	80906.92
23	71326.90	65939.06	66255.51	66557.46	67275.71	68053.49	68322.18	68856.37	69183.66	69387.86
24	71210.30	65720.89	66099.85	66461.99	67255.37	68009.71	68225.42	68725.19	69021.80	69206.72
25	63809.60	59782.31	59911.49	60033.43	60483.45	61010.38	61167.24	61570.27	61805.84	61952.07
26	63707.80	59582.61	59761.08	59930.45	60443.85	60989.02	61110.69	61477.05	61669.00	61792.39
27	63604.70	59381.20	59611.31	59830.40	60408.74	60973.05	61061.14	61391.35	61549.49	61636.89
28	43023.30	40193.39	40190.72	40186.12	40427.57	40759.86	40810.00	41072.84	41184.94	41239.68
29	42916.00	40046.11	40080.18	40110.90	40403.96	40744.33	40767.66	40999.38	41083.82	41116.61
30	42791.00	39817.59	39956.78	40025.38	40371.80	40721.22	40719.57	40920.75	40978.94	40991.20
31	37773.20	35807.48	35749.15	35691.38	35821.95	36041.50	36019.82	36171.44	36201.22	36195.38
32	37611.50	35716.92	35684.78	35652.12	35819.00	35998.71	35959.27	36084.67	36094.54	36073.90
33	29370.10	27831.88	27752.34	27674.28	27761.98	27902.48	27848.71	27948.16	27940.68	27907.85
34	25590.00	24498.60	24427.28	24358.13	24374.26	24463.87	24408.48	24473.26	24454.74	24418.57
35	25312.10	24497.53	24413.29	24331.33	24354.07	24404.83	24348.17	24390.64	24365.32	24327.03
36	24990.40	24491.67	24409.60	24329.47	24348.14	24380.00	24332.43	24353.50	24329.31	24296.71

Table 4.5 Axial Force in Cables under Cable Losses (Cable 1 to 9)

Cable	Axial Force (kN)								
1	93143.17	92843.28	92578.57	92355.76	92238.98	92058.57	91961.21	91905.80	91858.68
2	93072.27	92769.79	92499.67	92268.62	92148.92	91953.81	91847.54	91786.44	91732.55
3	93004.85	92699.55	92423.54	92183.48	92060.58	91849.38	91733.33	91666.00	91604.72
4	83880.38	83602.26	83347.48	83122.00	83008.00	82801.51	82687.13	82620.21	82557.59
5	72489.21	72208.68	71948.02	71713.14	71595.90	71372.14	71247.23	71173.61	71102.99
6	72437.48	72155.08	71888.60	71643.88	71523.35	71280.91	71144.60	70942.57	70984.35
7	64966.59	64712.38	64468.39	64239.75	64128.75	63893.16	63759.82	63680.15	63600.41
8	64916.21	64662.83	64414.93	64177.50	64063.98	63809.35	63664.27	63577.07	63488.11
9	64858.21	64608.09	64357.92	64112.42	63997.04	63722.56	63565.16	63470.01	63371.18
10	Removed	48494.59	48271.75	48046.91	47943.29	47680.48	47528.78	47436.58	47339.11
11	44068.17	Removed	48200.16	47971.81	47868.99	47588.62	47425.69	47326.14	47219.01
12	43929.84	43756.71	Removed	43339.07	43239.32	42942.92	42769.43	42662.86	42546.06
13	38753.80	38613.65	38457.78	Removed	38196.14	37922.30	37760.74	37660.94	37549.37
14	35844.62	38418.41	38275.72	38107.52	Removed	37772.29	37605.70	37502.20	37383.85
15	30232.12	30121.02	29993.23	29838.49	29794.46	Removed	29370.70	29266.52	29144.17
16	26259.67	26176.88	26079.93	25959.30	25930.58	25720.57	Removed	25508.78	25402.25
17	25862.83	25797.19	25718.94	25618.90	25600.03	25417.88	25311.32	Removed	25151.78
18	25388.60	25343.06	25287.94	25215.64	25206.27	25068.59	24989.33	24945.96	Removed
19	90991.05	91259.59	91494.76	91690.19	91795.16	91947.06	92029.34	92077.83	92118.72
20	90797.92	91065.34	91302.11	91502.00	91608.01	91770.51	91859.41	91912.30	91958.81
21	90604.71	90871.04	91109.66	91314.52	91421.73	91595.89	91692.07	91749.79	91802.46
22	81597.38	81836.71	82053.92	82243.75	82341.71	82510.43	82604.44	82661.33	82714.96
23	70086.50	70324.54	70543.67	70738.84	70838.06	71019.38	71121.27	71183.40	71243.71
24	69913.31	70149.56	70370.48	70571.24	70671.73	70866.69	70977.13	71044.98	71112.60
25	62592.34	62802.00	63001.50	63186.76	63277.97	63466.07	63573.46	63639.90	63707.73
26	62436.52	62642.52	62842.47	63032.58	63124.53	63326.49	63442.66	63515.04	63590.59
27	62280.96	62481.41	62680.52	62874.83	62967.02	63183.30	63308.65	63387.29	63471.11
28	41800.32	41971.73	42146.77	42322.76	42404.48	42610.21	42730.35	42806.27	42888.81
29	41665.83	41820.36	41990.18	42166.99	42247.10	42465.05	42593.34	42675.03	42765.59
30	41525.72	41668.21	41823.16	41997.97	42074.88	42303.51	42439.22	42526.38	42624.92
31	36652.02	36767.21	36894.99	37040.00	37103.34	37312.67	37438.10	37519.46	37613.31
32	36508.17	36611.70	36729.04	36866.15	36918.75	37130.27	37258.43	37342.55	37441.72
33	28311.38	28402.21	28507.57	28634.39	28679.20	28882.93	29009.61	29094.05	29196.01
34	24734.86	24802.04	24881.97	24981.12	25013.47	25180.05	25283.43	25354.38	25442.46
35	24587.52	24639.77	24703.73	24785.56	24810.59	24953.68	25043.08	25105.82	25185.66
36	24476.44	24510.60	24553.97	24611.25	24628.63	24732.16	24797.91	24845.89	24909.43

Table 4.6 Axial Force in Cables under Cable Losses (Cable 10 to 18)

Cable	Axial Force (kN)								
1	84868.49	85560.10	86215.25	87339.98	88394.75	88810.91	89471.89	89789.38	90080.63
2	85029.68	85632.31	86223.22	87283.43	88290.74	88676.73	89314.84	89614.43	89891.74
3	85206.29	85735.59	86241.69	87231.51	88187.04	88540.10	89153.25	89433.32	89695.42
4	77069.22	77482.66	77877.41	78687.25	79498.10	79784.10	80312.58	80545.96	80767.39
5	65908.97	66260.26	66595.03	67333.32	68074.19	68323.96	68824.50	69036.32	69240.89
6	66089.68	66381.03	66657.99	67325.46	68006.49	68204.72	68673.34	68860.88	69046.38
7	59478.15	59687.91	59886.63	60423.10	60980.89	61123.30	61500.50	61643.99	61790.87
8	59636.94	59797.13	59948.06	60423.11	60927.96	61036.35	61378.90	61484.62	61608.72
9	59790.32	59902.85	60008.19	60423.15	60875.74	60951.66	61260.00	61337.76	61425.84
10	44383.97	44444.47	44499.70	44817.63	45175.43	45215.63	45460.50	45506.21	45561.45
11	44501.60	44524.14	44542.89	44809.98	45122.66	45136.91	45352.12	45375.40	45408.63
12	40065.99	40053.06	40037.74	40255.51	40523.85	40513.88	40699.88	40702.21	40174.74
13	35564.52	35524.32	35483.13	35633.84	35832.90	35804.48	35943.74	35928.77	35922.97
14	35616.93	35551.41	35485.97	35596.18	35622.00	35711.60	35825.64	35795.64	35774.81
15	27607.58	27521.59	27436.64	27508.55	27632.10	27572.74	27661.81	27619.54	27586.27
16	24273.76	24186.63	24101.09	24133.45	24209.78	24149.99	24206.57	24162.32	24125.53
17	24276.82	24188.14	24101.47	24107.58	24152.91	24092.47	24127.87	24082.18	24043.09
18	24307.84	24232.85	24159.89	24147.46	24164.62	24114.08	24129.69	24091.18	24057.78
19	Removed	98927.85	98271.03	97083.36	95952.09	95521.41	94803.06	94466.92	94154.73
20	99188.20	Removed	98020.77	96894.68	95805.65	95405.17	94705.04	94385.69	94085.86
21	98745.47	98245.52	Removed	96703.27	95661.44	95294.47	94614.84	94314.17	94028.15
22	88707.88	88324.77	87953.76	Removed	86205.33	85908.00	85315.87	85063.21	84819.48
23	76952.04	76634.41	76327.25	75544.22	Removed	74475.86	73908.68	73678.02	73450.24
24	76527.94	76273.03	76027.02	75316.62	74568.13	Removed	73840.32	73634.82	73426.06
25	68299.88	68124.81	67956.35	67382.90	66765.61	66633.47	Removed	66049.60	65882.53
26	67910.92	67786.89	67668.17	67157.58	66594.38	66499.23	66109.69	Removed	65863.11
27	67517.20	67441.44	67369.73	66920.53	66410.84	66350.69	65997.25	65924.63	Removed
28	46251.53	46224.40	46199.83	45852.46	45444.89	45420.61	45137.16	45098.81	45046.35
29	45879.80	45890.31	45902.38	45606.75	45245.57	45248.65	44996.60	44983.00	44955.62
30	45486.96	45531.97	45577.62	45332.02	45016.52	45044.74	44823.68	44832.96	44828.88
31	39919.33	39986.48	40053.45	39878.55	39638.91	39683.86	39515.15	39541.70	39556.89
32	39508.02	39598.27	39687.70	39553.51	39353.15	39415.10	39273.23	39315.67	39347.36
33	31005.02	31112.70	31219.04	31123.06	30961.40	31036.34	30921.07	30976.09	31021.21
34	26781.75	26884.50	26985.77	26931.86	26823.06	26895.28	26817.07	26872.30	26919.84
35	26238.13	26338.22	26436.80	26408.39	26331.51	26402.50	26346.76	26402.63	26452.21
36	25268.81	25710.53	25791.08	25780.12	25732.17	25790.83	25755.96	25803.27	25846.27

Table 4.7 Axial Force in Cables under Cable Losses (Cable 19 to 27)

Cable	Axial Force (kN)									
1	90080.63	90813.66	91078.82	91310.56	91503.21	91606.22	91755.79	91837.19	91885.17	91962.08
2	89891.74	90633.58	90898.28	91132.21	91329.90	91434.24	91594.92	91683.28	91735.88	91782.63
3	89695.42	90446.85	90711.04	90947.36	91150.54	91256.34	91429.12	91525.08	91582.72	91635.84
4	80767.39	81454.75	81692.60	81908.16	82096.88	82193.76	82361.60	82455.66	82512.65	82566.88
5	69240.89	69937.61	70174.55	70392.34	70586.79	70685.12	70865.86	70968.03	71030.43	71091.51
6	69046.38	69752.03	69987.49	70207.40	70407.69	70507.43	70702.07	70813.00	70881.27	70949.83
7	61790.87	62431.00	62640.14	62838.93	63023.99	63114.62	63302.61	63410.61	63477.55	63546.37
8	61608.72	62253.20	62458.82	62658.19	62848.25	62939.70	63141.67	63258.60	63331.59	63408.26
9	61425.84	62070.56	62270.68	62469.27	62663.63	62755.35	62971.73	63097.96	63177.31	63262.37
10	45561.45	46122.76	46293.87	46468.44	46644.51	46725.80	46931.64	47052.65	47129.27	47213.03
11	45408.63	45958.37	46112.49	46281.77	46458.63	46538.29	46756.32	46885.52	46967.98	47059.85
12	40174.74	41249.49	41391.43	41545.68	41720.45	41796.84	42025.47	42162.13	42250.09	42350.00
13	35922.97	36379.40	36493.93	36620.93	36765.75	36828.55	37037.76	37164.00	37246.09	37341.21
14	35774.81	36208.28	36310.95	36427.32	36564.07	36616.00	36827.23	36956.14	37040.98	37141.42
15	27586.27	27988.32	28078.06	28182.24	28308.51	28352.54	28555.77	28683.10	28768.20	28871.41
16	24125.53	24439.89	24505.93	24584.67	24683.17	24714.77	24880.73	24984.53	25055.99	25145.07
17	24043.09	24301.20	24352.21	24414.92	24495.97	24520.25	24662.61	24752.28	24815.41	24896.08
18	24057.78	24235.11	24268.15	24310.41	24366.95	24383.70	24486.55	24552.41	24600.64	24664.76
19	94154.73	93311.45	93010.68	92744.38	92519.14	92400.72	92218.02	92118.73	92061.99	92013.91
20	94085.86	93222.23	92918.30	92646.09	92412.20	92290.64	92093.05	91984.68	91922.14	91867.21
21	94028.15	93142.82	92835.51	92556.99	92313.75	92188.82	91974.99	91856.71	91787.84	91725.41
22	84819.48	83999.78	83719.45	83462.11	83233.52	83117.56	82908.62	82792.11	82723.72	82659.98
23	73450.24	72609.28	72326.25	72062.88	71824.65	71705.37	71479.11	71352.00	71276.83	71205.00
24	73426.06	72564.07	72278.96	72009.59	71761.46	71638.87	71393.93	71255.35	71172.84	71092.19
25	65882.53	65091.30	64834.57	64587.95	64356.22	64243.36	64005.59	63870.15	63789.00	63708.01
26	65863.11	65057.18	64801.27	64550.79	64310.29	64194.98	63938.26	63791.06	63702.34	63612.05
27	Removed	65020.41	64767.87	64515.24	64266.78	64149.70	63873.28	63713.75	63617.06	63516.81
28	45046.35	Removed	48660.32	48435.50	48208.18	48103.17	47838.81	47685.24	47591.65	47492.83
29	44955.62	44261.80	Removed	48390.44	48159.84	48055.83	47774.13	47609.37	47508.43	47399.88
30	44828.88	44151.64	43977.21	Removed	43556.41	43455.70	43158.26	42983.02	42875.08	42756.79
31	39556.89	38977.02	38836.07	38679.50	Removed	38416.04	38141.58	37978.56	37877.60	37764.65
32	39347.36	38794.70	38668.14	38525.21	38356.18	Removed	38020.54	37852.63	37748.02	37628.26
33	31021.21	30505.84	30394.88	30267.34	30112.24	30068.38	Removed	29643.78	29538.61	29414.84
34	26919.84	26512.54	26430.32	26334.02	26213.51	26185.19	25975.77	Removed	25762.64	25654.91
35	26452.21	26109.24	26044.53	25967.30	25867.75	25849.51	25668.21	25561.32	Removed	25400.29
36	25846.27	25593.02	25548.58	25494.62	25423.01	25414.36	25277.61	25198.25	25154.69	Removed

Table 4.8 Axial Force in Cables under Cable Losses (Cable 27 to 36

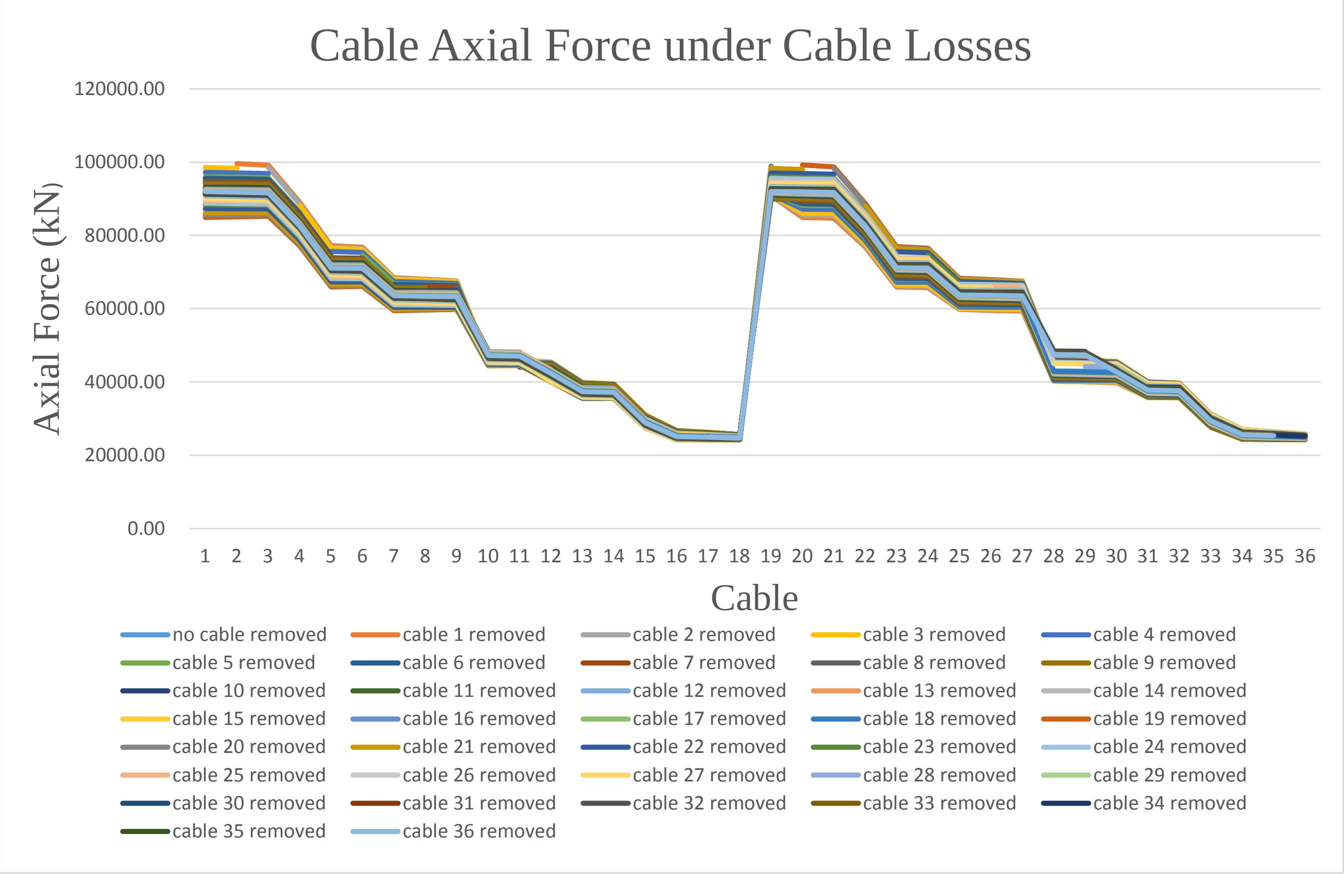


Figure 4.8 Cable Axial Force Under Cable Losses

The data shows that when the cable of a side of the bridge was removed, the cable axial forces of the cables from the same side of the bridge were increased. The further the removed cable from the pylon, the higher the increment of cable axial forces in the other cables. The cables located further from pylon are considered as the more critical cables as they having higher axial force. By removing these critical cables, the other cables are more likely to rupture and eventually causing progressive collapse.

4.3.2 Stresses in Pylon and Bridge Deck under Cable Losses

Table 4.9 to 4.10 and figure 4.9 to 4.10 show the stresses in pylon and bridge deck when the cable was removed one at a time.

Cable Removed	The Decrease in Stress of Pylon (%)	Cable Removed	The Decrease in Stress of Pylon (%)
1	-9.25	19	-14.13
2	-8.76	20	-12.98
3	-7.80	21	-11.37
4	-7.53	22	-9.75
5	-6.99	23	-8.53
6	-6.80	24	-7.07
7	-5.88	25	-6.99
8	-5.68	26	-5.84
9	-5.61	27	-5.53
10	-4.69	28	-5.30
11	-4.65	29	-4.76
12	-4.34	30	-4.72
13	-3.46	31	-4.22
14	-3.38	32	-4.07
15	-1.88	33	-3.76
16	-1.61	34	-3.34
17	-1.57	35	-2.11
18	-1.50	36	-1.23

Table 4.9 Decrease in Stress of Pylon under Cable Losses

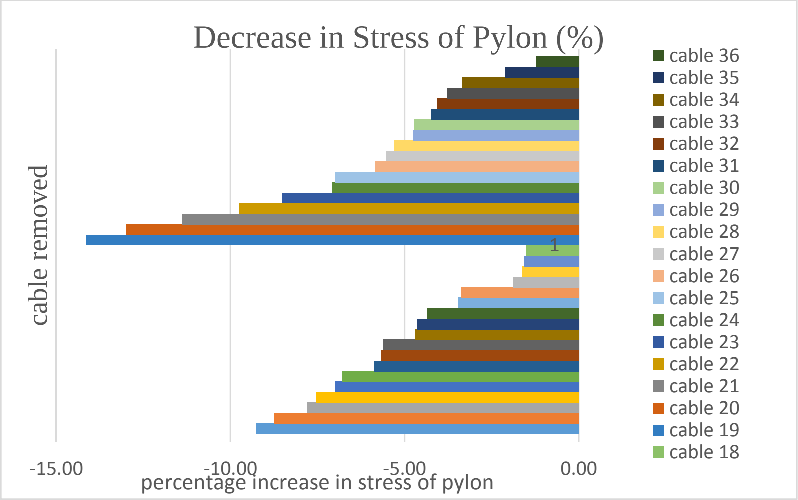


Figure 4.9 Decrease in Stress of Pylon under Cable Losses

Cable Removed	The Decrease in Stress of Left Side Span of Deck (%)	The Decrease in Stress of Mid Span of Deck (%)
1	-4.69	-11.11
2	-4.40	-10.70
3	-4.40	-10.70
4	-4.40	-10.70
5	-4.11	-9.88
6	-4.11	-9.47
7	-4.11	-8.64
8	-3.81	-8.64
9	-3.81	-8.23
10	-2.93	-5.76
11	-2.93	-4.94
12	-2.35	-4.12
13	-2.05	-2.88
14	-2.05	-2.47
15	-1.17	-1.65
16	-1.17	-1.23
17	-0.88	-0.82
18	-0.59	-0.82
19	-6.16	-15.23
20	-5.87	-14.40
21	-5.87	-11.93
22	-4.99	-11.93
23	-3.81	-11.52
24	-3.81	-11.11
25	-3.23	-11.11
26	-3.23	-9.47
27	-2.64	-8.23

28	-1.76	-4.94
29	-1.47	-3.70
30	-1.17	-2.88
31	-0.88	-2.06
32	-0.88	-1.65
33	-0.59	-0.82
34	-0.59	-0.82
35	-0.59	-0.82
36	-0.29	-0.41

Table 4.10 Decrease in Stress of Deck under Cable Losses

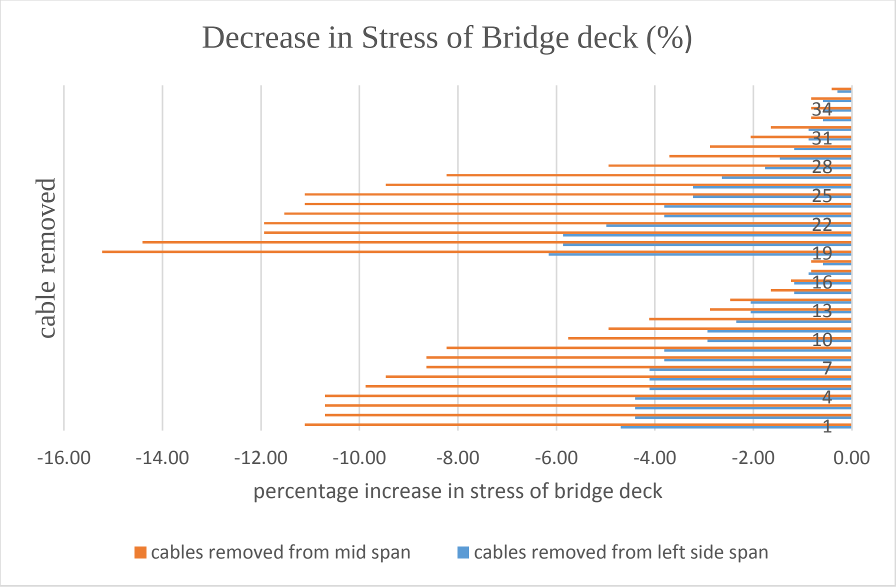


Figure 4.10 Decrease in Stress of Deck under Cable Losses

The stresses in the pylon and bridge deck were decrease when the cables were removed from the bridge. The further the removed cable from the pylon, the higher the percentage decrease of stresses in bridge deck and cables. Removing the cable which located further from the pylon will cause a higher percentage decrease of stress in bridge deck and pylon.

4.4 Progressive Collapse Analysis

The effect of cable losses on the cables has been shown above. When a cable was removed, a load redistribution will occur among the cables. The axial force increment will increase the probability of a cable to be a rupture and causing the failure of the whole bridge structure. The cable with the highest increment of axial force is the most rupture and vulnerable to progressive collapse.

In this study, the progressive collapse analysis is carried out on the left part of the model bridge (cable 1 – 36). The most vulnerable cable was found by identifying the cable with the highest percentage increase in axial forces whenever a cable was being removed. The percentage difference in cable axial force of every cable under cable losses are recorded as shown in Tables 4.11 to 4.13. The cable with the highest percentage increase in axial forces for each case is highlighted. The most vulnerable cables on each case are then shown in Table 4.14.

Cable	Difference in Axial Force (%)											
1	Removed	8.14	7.35	5.94	4.61	4.10	3.26	2.74	2.39	1.48	1.15	0.86
2	8.65	Removed	7.23	5.90	4.61	4.14	3.33	2.82	2.49	1.56	1.23	0.93
3	8.31	7.69	Removed	5.84	4.62	4.18	3.39	2.92	2.60	1.64	1.31	1.01
4	7.95	7.42	6.90	Removed	4.62	4.22	3.46	3.02	2.72	1.74	1.40	1.09
5	8.78	8.26	7.77	6.57	Removed	4.94	4.10	3.63	3.31	2.13	1.74	1.37
6	8.34	7.91	7.51	6.42	5.28	Removed	4.19	3.75	3.46	2.26	1.86	1.48
7	7.89	7.55	7.23	6.25	5.21	4.97	Removed	3.88	3.62	2.39	1.99	1.60
8	7.43	7.18	6.95	6.07	5.12	4.94	4.29	Removed	3.78	2.52	2.12	1.73
9	6.97	6.80	6.65	5.87	5.01	4.89	4.30	4.07	Removed	2.66	2.26	1.87
10	8.02	7.90	7.80	6.96	6.00	5.92	5.26	5.04	4.93	Removed	2.99	2.49
11	7.44	7.41	7.40	6.68	5.82	5.80	5.21	5.07	5.01	3.48	Removed	2.66
12	5.59	5.65	5.72	5.09	4.31	4.35	3.81	3.72	3.71	2.15	1.75	Removed
13	6.69	6.83	6.98	6.46	5.77	5.87	5.39	5.36	5.41	3.86	3.49	3.07
14	6.01	6.22	6.43	6.03	5.44	5.60	5.19	5.22	5.30	-3.45	3.48	3.10
15	6.67	7.02	7.36	6.98	6.37	6.61	6.19	6.28	6.44	4.66	4.27	3.83
16	5.73	6.12	6.50	6.25	5.77	6.05	5.71	5.85	6.04	4.42	4.09	3.71
17	4.58	4.96	5.35	5.20	4.86	5.13	4.89	5.05	5.25	3.87	3.60	3.29
18	3.24	3.56	3.88	3.81	3.59	3.82	3.67	3.83	4.00	2.96	2.78	2.55
19	-1.33	-1.22	-1.12	-0.96	-0.88	-0.81	-0.70	-2.39	-2.07	-1.27	-0.98	-0.72
20	-7.69	-7.08	-6.49	-5.29	-4.11	-3.66	-2.92	-2.43	-2.13	-1.32	-1.03	-0.77
21	-7.56	-6.86	-6.17	-4.98	-3.85	-3.44	-2.73	-2.27	-1.98	-1.16	-0.87	-0.60
22	-7.17	-6.64	-6.12	-5.07	-4.02	-3.65	-2.97	-2.54	-2.27	-1.44	-1.15	-0.89
23	-7.55	-7.11	-6.69	-5.68	-4.59	-4.21	-3.46	-3.00	-2.72	-1.74	-1.41	-1.10
24	-7.71	-7.18	-6.67	-5.55	-4.49	-4.19	-3.49	-3.07	-2.81	-1.82	-1.49	-1.18
25	-6.31	-6.11	-5.92	-5.21	-4.39	-4.14	-3.51	-3.14	-2.91	-1.91	-1.58	-1.27
26	-6.48	-6.20	-5.93	-5.12	-4.27	-4.08	-3.50	-3.20	-3.01	-2.00	-1.67	-1.36
27	-6.64	-6.28	-5.93	-5.02	-4.14	-4.00	-3.48	-3.23	-3.09	-2.08	-1.77	-1.45
28	-6.58	-6.58	-6.59	-6.03	-5.26	-5.14	-4.53	-4.27	-4.15	-2.84	-2.44	-2.04
29	-6.69	-6.61	-6.54	-5.85	-5.06	-5.01	-4.47	-4.27	-4.19	-2.91	-2.55	-2.16
30	-6.95	-6.62	-6.46	-5.65	-4.84	-4.84	-4.37	-4.23	-4.21	-2.96	-2.62	-2.26
31	-5.20	-5.36	-5.51	-5.17	-4.58	-4.64	-4.24	-4.16	-4.18	-2.97	-2.66	-2.32
32	-5.04	-5.12	-5.21	-4.77	-4.29	-4.39	-4.06	-4.03	-4.09	-2.93	-2.66	-2.35
33	-5.24	-5.51	-5.77	-5.48	-5.00	-5.18	-4.84	-4.87	-4.98	-3.60	-3.30	-2.94
34	-4.26	-4.54	-4.81	-4.75	-4.40	-4.62	-4.36	-4.44	-4.58	-3.34	-3.08	-2.77
35	-3.22	-3.55	-3.87	-3.78	-3.58	-3.81	-3.64	-3.74	-3.89	-2.86	-2.66	-2.40
36	-2.00	-2.32	-2.64	-2.57	-2.44	-2.63	-2.55	-2.65	-2.78	-2.06	-1.92	-1.75

Table 4.11 Difference in Axial Force under Cable Losses (Cable 1 to 12)

Cable Difference in Axial Force (%)

Cable	Difference in Axial Force (%)											
1	0.62	0.49	0.30	0.19	0.13	-0.08	-7.54	-6.78	-6.07	-4.84	-3.69	-3.24
2	0.68	0.55	0.34	0.22	0.15	-0.10	-7.22	-6.56	-5.92	-4.76	-3.66	-3.24
3	0.75	0.61	0.38	0.25	0.18	-0.11	-6.88	-6.30	-5.75	-4.67	-3.62	-3.24
4	0.82	0.68	0.43	0.29	0.21	-0.13	-6.52	-6.02	-5.54	-4.56	-3.58	-3.23
5	1.04	0.87	0.56	0.38	0.28	-0.18	-7.14	-6.65	-6.17	-5.13	-4.09	-3.74
6	1.14	0.97	0.62	0.43	0.15	-0.20	-6.70	-6.29	-5.90	-4.96	-4.00	-3.72
7	1.24	1.07	0.70	0.49	0.36	-0.23	-6.26	-5.93	-5.62	-4.77	-3.89	-3.67
8	1.36	1.18	0.77	0.55	0.41	-0.27	-5.81	-5.56	-5.32	-4.57	-3.78	-3.60
9	1.48	1.29	0.86	0.61	0.46	-0.30	-5.36	-5.19	-5.02	-4.36	-3.65	-3.53
10	1.99	1.77	1.18	0.85	0.64	0.43	-6.12	-5.98	-5.86	-5.16	-4.37	-4.28
11	2.15	1.92	1.30	0.94	0.72	0.48	-5.56	-5.51	-5.47	-4.87	-4.18	-4.15
12	0.78	0.54	-0.23	0.37	0.22	0.21	-4.51	-4.54	-4.57	-4.07	-3.44	-3.47
13	Removed	2.37	1.63	1.20	0.93	-0.63	-4.69	-4.79	-4.90	-4.50	-3.97	-4.04
14	2.64	Removed	1.74	1.29	1.01	-0.69	-4.06	-4.24	-4.42	-4.12	-4.05	-3.81
15	3.29	3.14	Removed	1.68	1.31	-0.88	-4.43	-4.73	-5.02	-4.77	-4.34	-4.55
16	3.23	3.11	2.28	Removed	1.44	-1.00	-3.48	-3.82	-4.16	-4.03	-3.73	-3.97
17	2.89	2.81	2.08	1.65	Removed	-1.00	-2.50	-2.86	-3.21	-3.18	-3.00	-3.24
18	2.26	2.22	1.66	1.34	1.17	Removed	-1.42	-1.73	-2.02	-2.07	-2.00	-2.21
19	-0.51	-0.39	-0.23	-0.14	-0.09	0.04	Removed	7.35	6.63	5.34	4.12	3.65
20	-0.55	-0.44	-0.26	-0.16	-0.11	0.06	7.80	Removed	6.53	5.31	4.13	3.69
21	-0.38	-0.26	-0.07	0.03	0.09	-0.15	7.73	7.18	Removed	5.50	4.36	3.96
22	-0.66	-0.54	-0.34	-0.22	-0.15	0.09	7.15	6.69	6.24	Removed	4.13	3.77
23	-0.82	-0.69	-0.43	-0.29	-0.20	0.12	7.89	7.43	7.01	5.91	Removed	4.41
24	-0.90	-0.76	-0.48	-0.33	-0.23	0.14	7.47	7.11	6.76	5.77	4.72	Removed
25	-0.98	-0.83	-0.54	-0.37	-0.27	0.16	7.04	6.76	6.50	5.60	4.63	4.43
26	-1.06	-0.92	-0.60	-0.42	-0.30	0.18	6.60	6.40	6.22	5.42	4.53	4.38
27	-1.15	-1.00	-0.66	-0.47	-0.34	0.21	6.15	6.03	5.92	5.21	4.41	4.32
28	-1.63	-1.44	-0.96	-0.68	-0.50	0.31	7.50	7.44	7.38	6.58	5.63	5.57
29	-1.75	-1.56	-1.05	-0.75	-0.56	0.35	6.91	6.93	6.96	6.27	5.43	5.44
30	-1.85	-1.67	-1.14	-0.82	-0.62	0.39	6.30	6.41	6.51	5.94	5.20	5.27
31	-1.94	-1.77	-1.22	-0.89	-0.67	0.43	5.68	5.86	6.04	5.57	4.94	5.06
32	-1.98	-1.84	-1.28	-0.94	-0.72	0.45	5.04	5.28	5.52	5.16	4.63	4.80
33	-2.50	-2.35	-1.66	-1.23	-0.94	0.60	5.57	5.93	6.30	5.97	5.42	5.67
34	-2.38	-2.25	-1.60	-1.20	-0.92	0.58	4.66	5.06	5.45	5.24	4.82	5.10
35	-2.08	-1.98	-1.42	-1.06	-0.81	0.50	3.66	4.05	4.44	4.33	4.03	4.31
36	-1.52	-1.45	-1.03	-0.77	-0.58	0.33	1.11	2.88	3.20	3.16	2.97	3.20

Table 4.12 Difference in Axial Force under Cable Losses (Cable 13 to 24)

1	-2.52	-2.17	-1.86	-1.06	-0.11	-0.52	-0.31	-0.20	-0.03	0.06	0.11	0.19
2	-2.54	-2.22	-1.91	-1.10	-0.10	-0.56	-0.34	-0.23	-0.05	0.04	0.10	0.15
3	-2.57	-2.26	-1.97	-1.15	-0.11	-0.61	-0.38	-0.27	-0.08	0.03	0.09	0.15
4	-2.59	-2.31	-2.04	-1.21	-0.12	-0.66	-0.43	-0.31	-0.11	0.01	0.08	0.14
5	-3.03	-2.73	-2.45	-1.46	-0.14	-0.82	-0.55	-0.41	-0.16	-0.01	0.08	0.16
6	-3.06	-2.79	-2.53	-1.53	-0.14	-0.89	-0.61	-0.47	-0.19	-0.04	0.06	0.16
7	-3.08	-2.85	-2.62	-1.61	-0.16	-0.97	-0.67	-0.53	-0.23	-0.06	0.04	0.15
8	-3.06	-2.90	-2.70	-1.68	-0.16	-1.04	-0.74	-0.60	-0.28	-0.10	0.02	0.14
9	-3.04	-2.92	-2.78	-1.76	-0.16	-1.12	-0.82	-0.67	-0.33	-0.13	0.00	0.13
10	-3.73	-3.63	-3.51	-2.27	-1.89	-1.50	-1.11	-0.93	-0.48	-0.21	-0.04	0.15
11	-3.67	-3.62	-3.54	-2.32	-1.98	-1.60	-1.21	-1.03	-0.55	-0.26	-0.08	0.13
12	-3.04	-3.03	-4.26	-1.76	-1.43	-1.07	-0.66	-0.48	0.05	0.37	0.57	0.80
13	-3.67	-3.71	-3.73	-2.50	-0.27	-1.86	-1.47	-1.30	-0.74	-0.40	-0.18	0.08
14	-3.50	-3.58	-3.64	-2.47	-0.28	-1.88	-1.51	-1.37	-0.80	-0.46	-0.23	0.04
15	-4.24	-4.39	-4.50	-3.11	-0.36	-2.44	-2.00	-1.85	-1.15	-0.71	-0.41	-0.05
16	-3.74	-3.92	-4.07	-2.82	-0.41	-2.24	-1.85	-1.72	-1.06	-0.65	-0.37	-0.01
17	-3.10	-3.28	-3.44	-2.40	-0.41	-1.95	-1.62	-1.52	-0.95	-0.59	-0.34	-0.01
18	-2.14	-2.30	-2.44	-1.72	-0.41	-1.41	-1.18	-1.11	-0.70	-0.43	-0.23	0.03
19	2.87	2.50	2.17	1.25	0.11	0.64	0.39	0.26	0.06	-0.04	-0.10	-0.16
20	2.93	2.58	2.26	1.32	0.11	0.69	0.44	0.30	0.09	-0.03	-0.10	-0.16
21	3.22	2.89	2.58	1.61	0.11	0.97	0.71	0.57	0.34	0.21	0.13	0.07
22	3.05	2.75	2.45	1.46	0.12	0.81	0.54	0.40	0.15	0.01	-0.08	-0.15
23	3.62	3.30	2.98	1.80	0.14	1.03	0.70	0.53	0.21	0.04	-0.07	-0.17
24	3.69	3.40	3.11	1.90	0.14	1.12	0.77	0.60	0.26	0.06	-0.05	-0.17
25	Removed	3.51	3.25	2.01	0.15	1.22	0.86	0.68	0.31	0.09	-0.03	-0.16
26	3.77	Removed	3.38	2.12	0.15	1.32	0.95	0.76	0.36	0.13	-0.01	-0.15
27	3.76	3.65	Removed	2.23	0.15	1.43	1.04	0.86	0.42	0.17	0.02	-0.14
28	4.91	4.82	4.70	Removed	0.20	0.96	0.43	0.19	-0.43	-0.79	-1.00	-1.23
29	4.85	4.82	4.75	3.14	Removed	1.11	0.57	0.33	-0.33	-0.71	-0.95	-1.20
30	4.75	4.77	4.76	3.18	0.23	Removed	1.79	1.55	0.86	0.45	0.20	-0.08
31	4.61	4.68	4.72	3.19	0.26	2.40	Removed	1.70	0.98	0.54	0.28	-0.02
32	4.42	4.53	4.62	3.15	0.26	2.43	1.98	Removed	1.09	0.64	0.36	0.04
33	5.28	5.47	5.62	3.87	0.33	3.05	2.53	2.38	Removed	0.93	0.57	0.15
34	4.80	5.01	5.20	3.61	0.38	2.91	2.44	2.33	1.51	Removed	0.67	0.25
35	4.09	4.31	4.50	3.15	0.38	2.59	2.20	2.12	1.41	0.98	Removed	0.35
36	3.06	3.25	3.42	2.41	0.39	2.02	1.73	1.70	1.15	0.83	0.66	Removed

Table 4.13 Difference in Axial Force under Cable Losses (Cable 27 to 36)

Cable Removed	Most Fragile Cable	Difference in Cable Axial Force (%)
1	2	8.65
2	5	8.26
3	5	7.77
4	15	6.98
5	15	6.37
6	15	6.61
7	15	6.19
8	15	6.28
9	15	6.44
10	15	4.66
11	15	4.27
12	15	3.83
13	15	3.29
14	15	3.14
15	16	2.28
16	15	1.68
17	16	1.44
18	36	0.39
19	23	7.89
20	28	7.44
21	28	7.38
22	28	6.58
23	28	5.63
24	33	5.67
25	33	5.28
26	33	5.47
27	33	5.62
28	33	3.87
29	2	-0.1
30	33	3.05
31	33	2.53
32	33	2.38
33	34	1.51
34	35	0.98
35	34	0.67
36	35	0.35

Table 4.14 The Most Fragile Cable under Cable Losses

From the progressive collapse analysis, the cable with the highest increase in the percentage of cable axial force during cable losses has been determined. The most fragile cable in cable losses is now known. When the failure of a particular cable happens, further action can be taken on the cable which most likely to rupture to prevent progressive collapse.

From Table 4.14, the highest increase in the cable axial force happens when the cable 1 was removed. The percentage increment in the cable axial force under cable losses is lower when the cable located nearer to the pylon is removed. This analysis has once again proved that the cables located further to the pylon are the more vital structural part in progressive collapse than the cables located at nearer to the pylon.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The side spans of the cable-stayed are more affected in a load translation as they have higher stress difference between the cables. When the uniform distributed load is applied on the bridge deck, the cables at side span of the bridge are having higher stresses differences than the cables at mid-span of the bridge. The side span of the bridge is playing a more crucial part in progressive collapse as they suffer from higher stresses.

When the cables are having a failure, the losing of cables will cause the stresses in pylon and bridge deck to be decreased. However the cable axial force of the remaining cables will be increased. The possibilities of the other cables to be rupture have increased and this will lead to the failure of the whole bridge structure and eventually causing progressive collapse.

The cables located furthest from the pylon are the most critical cables as they have the largest axial forces. Rupture of these cables will make the axial forces in the other cables increase the most and thus make the bridge more vulnerable to progressive collapse.

When cable-stayed bridge undergoes cable losses, the cable which its cable axial force increase the most have the highest probability to rupture and causing progressive collapse. By identifying the most fragile cables during cable losses and taking action on that particular cable, progressive collapse can be prevented.

5.2 Recommendation for the Future Research

1. Stimulation of moving load. In this study. Static load was used in the load application on the model bridge. By using the moving load, the finding of the stresses and an axial load of each cable will be more accurate. The result will be more relevant as it representing the moving vehicle in real life.
2. Consider the effect of wind load. By adding the factor of wind load in the stimulation, the result will be more relevant as the wind load will bring a high impact on the stress and axial load within the structure of the bridge.
3. Investigate the best cable arrangement against progressive collapse. In this study, the type of bridge model is a harp system. The fan and semi-fan cable arrangement can be used to identify the most stable cable arrangement.
4. Use varies type of cable in the stimulation. In this research, only one type of cable is used in the stimulation. The usage of other type of cable will manipulate the result as each cable have distinctive property which might affect the collapse mechanism.

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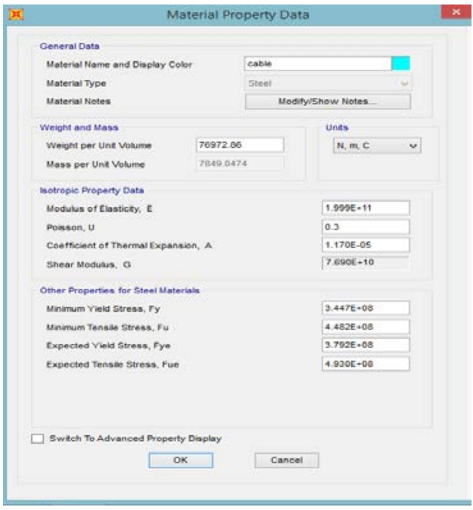
APPENDICES

Appendix A

MATERIAL PROPERTIES



General Data

Material Name and Display Color	cable
Material Type	Steel

Weight and Mass

Weight per Unit Volume	76972.86
Mass per Unit Volume	7849.0474

Units: N, m, C

Isotropic Property Data

Modulus of Elasticity, E	1.999E+11
Poisson, U	0.3
Coefficient of Thermal Expansion, A	1.170E-05
Shear Modulus, G	7.690E+10

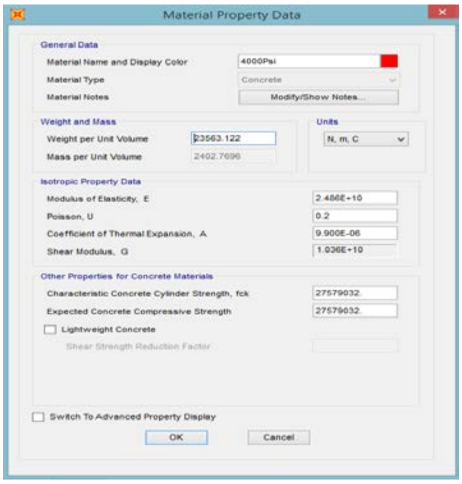
Other Properties for Steel Materials

Minimum Yield Stress, Fy	3.447E+08
Minimum Tensile Stress, Fu	4.482E+08
Expected Yield Stress, Fye	3.792E+08
Expected Tensile Stress, Fue	4.930E+08

☐ Switch To Advanced Property Display

,

Figure A1 Material Property of Concrete



General Data

Material Name and Display Color	4000Psi
Material Type	Concrete

Weight and Mass

Weight per Unit Volume	23563.122
Mass per Unit Volume	2402.7696

Units: N, m, C

Isotropic Property Data

Modulus of Elasticity, E	2.486E+10
Poisson, U	0.2
Coefficient of Thermal Expansion, A	9.900E-06
Shear Modulus, G	1.036E+10

Other Properties for Concrete Materials

Characteristic Concrete Cylinder Strength, fck	27579032
Expected Concrete Compressive Strength	27579032

☐ Lightweight Concrete

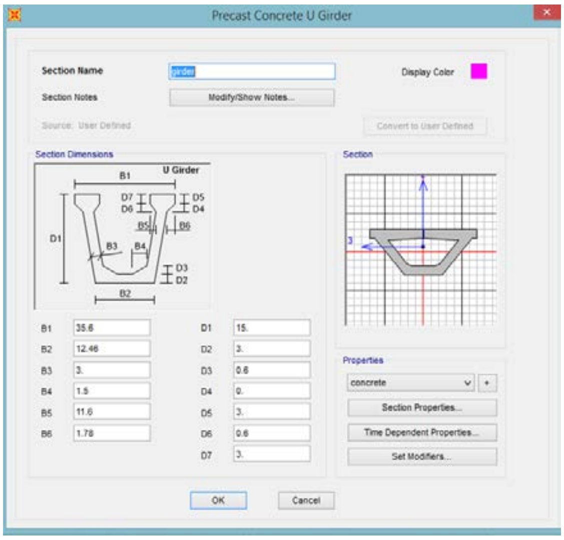
Shear Strength Reduction Factor

☐ Switch To Advanced Property Display

Figure A2 Material Property of Steel

Appendix B

SECTION PROPERTIES



Section Name: girder

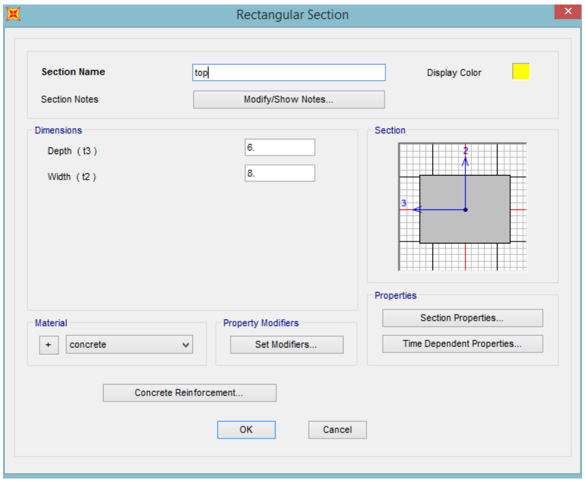
Section Notes

Source: User Defined

B1	35.6	D1	15.
B2	12.46	D2	3.
B3	3.	D3	0.6
B4	1.5	D4	0.
B5	11.6	D5	3.
B6	1.78	D6	0.6
		D7	3.

Properties: concrete

Figure B1 Properties of Concrete U Girder



Section Name: top

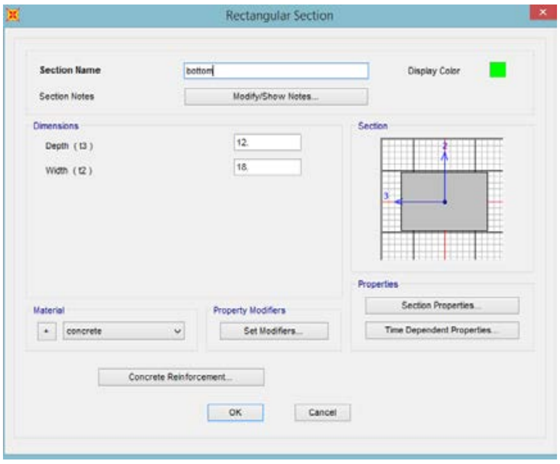
Section Notes

Depth (t3) 6.

Width (t2) 8.

Material: concrete

Figure B2 Properties of Top Pylon



Section Name: bottom

Display Color: 🟩

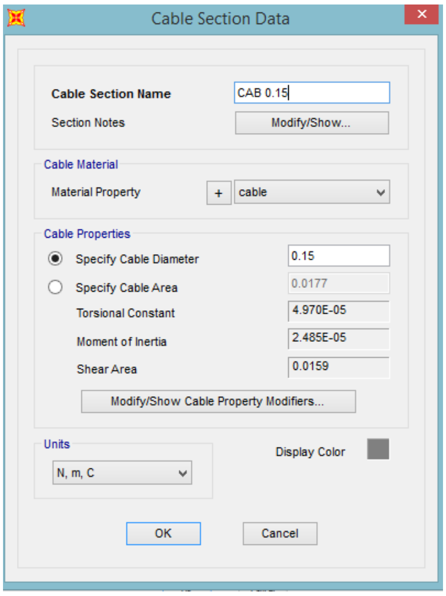
Dimensions

Depth (t3): 12.

Width (t2): 18.

Material: concrete

Figure B3 Properties of Bottom Pylon



Cable Section Name: CAB 0.15

Cable Material

Material Property: cable

Cable Properties

● Specify Cable Diameter: 0.15

○ Specify Cable Area: 0.0177

Torsional Constant: 4.970E-05

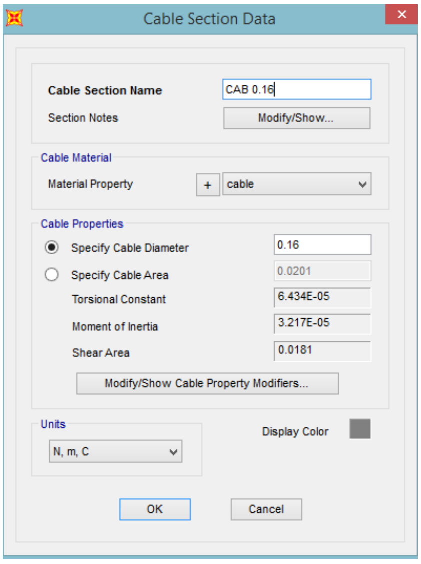
Moment of Inertia: 2.485E-05

Shear Area: 0.0159

Units: N, m, C

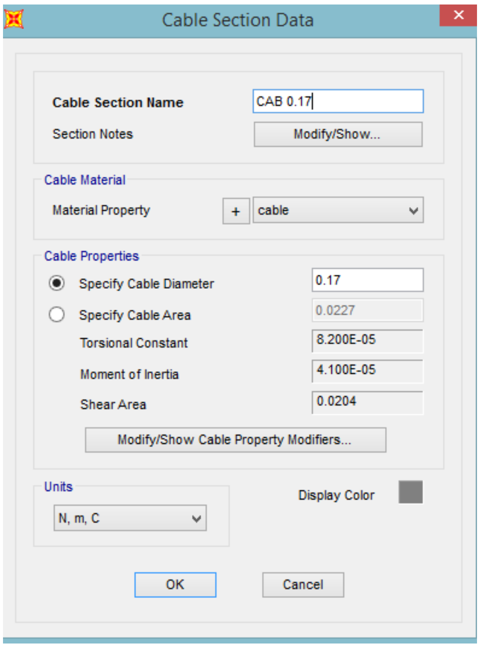
Display Color: ■

Figure B4 Properties of Cable with 0.15m diameter



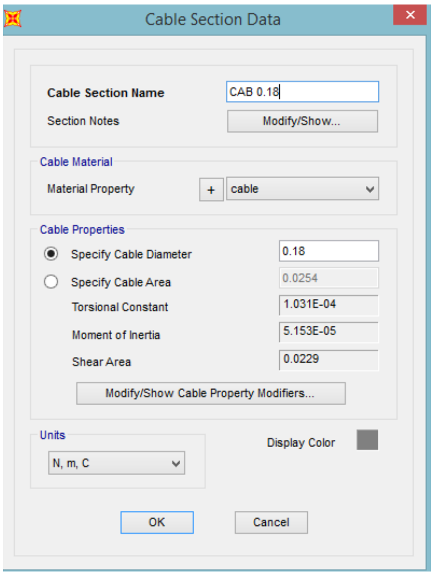
Cable Section Name CAB 0.16
Section Notes
Material Property: cable
● Specify Cable Diameter: 0.16
○ Specify Cable Area: 0.0201
Torsional Constant: 6.434E-05
Moment of Inertia: 3.217E-05
Shear Area: 0.0181
Units: N, m, C

Figure B5 Properties of Cable with 0.16m diameter



Cable Section Name CAB 0.17
Section Notes
Material Property: cable
● Specify Cable Diameter: 0.17
○ Specify Cable Area: 0.0227
Torsional Constant: 8.200E-05
Moment of Inertia: 4.100E-05
Shear Area: 0.0204
Units: N, m, C

Figure B6 Properties of Cable with 0.17m diameter



Cable Section Data

Cable Section Name CAB 0.18

Section Notes

Cable Material

Material Property: cable

Cable Properties

● Specify Cable Diameter: 0.18

○ Specify Cable Area: 0.0254

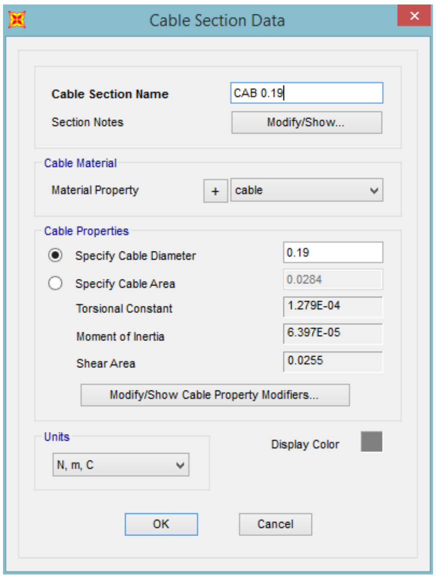
Torsional Constant: 1.031E-04

Moment of Inertia: 5.153E-05

Shear Area: 0.0229

Units: N, m, C

Figure B7 Properties of Cable with 0.18m diameter



Cable Section Data

Cable Section Name CAB 0.19

Section Notes

Cable Material

Material Property: cable

Cable Properties

● Specify Cable Diameter: 0.19

○ Specify Cable Area: 0.0284

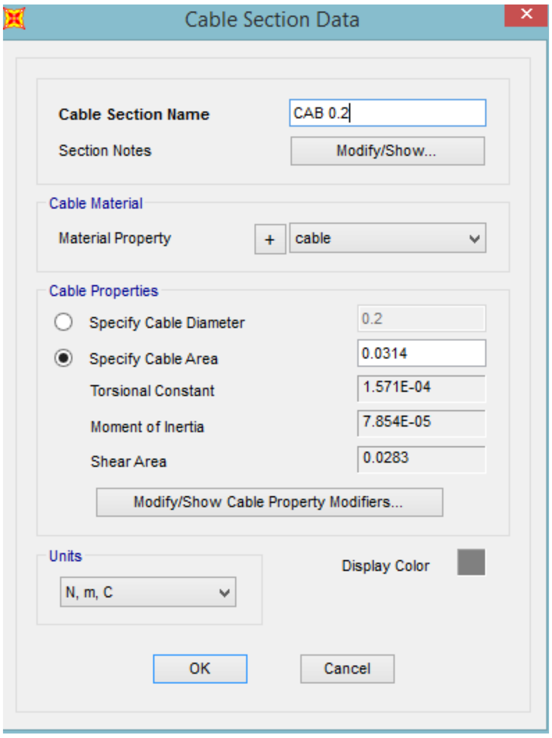
Torsional Constant: 1.279E-04

Moment of Inertia: 6.397E-05

Shear Area: 0.0255

Units: N, m, C

Figure B8 Properties of Cable with 0.19m diameter



Cable Section Name: CAB 0.2

Material Property: cable

○ Specify Cable Diameter: 0.2

● Specify Cable Area: 0.0314

Torsional Constant: 1.571E-04

Moment of Inertia: 7.854E-05

Shear Area: 0.0283

Units: N, m, C

Display Color: ■

Figure B9 Properties of Cable with 0.20m diameter