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Analysis of Damping System for Cable Stayed Bridges Under Dynamic Loading

A Thesis Submitted to Council of College of Engineering,
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for the Degree of Master of Science in Mechanical Engineering

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بسم الله الرحمن الرحيم

وَمَا أُوتِيتُمْ مِنْ الْعِلْمِ إِلاَّ قَلِيلاً (85)

صدق الله العظيم

سورة الاسراء

Dedication

I dedicate this work to my parents

My brothers

my friends

and to my country Iraq

ACKNOWLEDGMENTS

Sincere gratitude and appreciation are devoted to (**Asst. Prof. Dr. Ali Laftah Abbas**) and (**Dr. Eng. Zaid S. Hammoudi**) for their valuable advice and continuous encouragement throughout the work of this study.

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COMMITTEE DECISION

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ABSTRACT

The study deals with static, dynamic (earthquake response) analysis, and seismic analysis of cable stayed bridges. The analyses include the effect of using damping systems on the response of bridge to various directions of earthquakes.

The bridge of semi-fan type cables is considered in this study. Detailed analysis aspects of modeling, loading, boundary conditions (deck as simply supported beam and towers were fixed at base in all directions), and solution are presented in this study. Where, bridge's components were idealized as three dimensional modeling with shell, link and beam elements having six degree of freedoms. The cables are modeled in two schemes; First scheme as single link element, and second scheme as multi- beam elements.

Gravity load is applied on all nodes of cable stayed bridge. Accordingly, static and free vibration analyses of the cable stayed bridge are studied for cases of gravity load. It was found that, deflections of deck in first scheme were less than 30% those in second scheme. The results of first scheme were more realistic than those of the second's.

The cable stayed bridge is analyzed for earthquake excitations acting independently in three directions, longitudinal, transverse-horizontal and transverse- vertical directions. It was found that earthquakes in transverse- horizontal direction have greater effects on the bridge's deflections 50% than earthquakes in other directions because of its danger to the collapse of towers.

Damping effects on reduction deflections, resulted from earthquakes, are studied. The effect of changing number, direction and value of damping coefficient on reduction response to earthquake, are analyzed. Results show that inclined dampers were more effective than vertical dampers in longitudinal and lateral earthquakes. Damping effect of eight inclined dampers was 80% in deck deflections at lateral earthquake component. four vertical dampers have damping effect 50% on deck deflections with lateral earthquake

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K: is the stiffness matrix.

r: is the vector of applied loads.

u: is the vector of resulting displacements.

[C]: is the structural system damping matrix.

α: the parameter which define damping matrix.

[M]: structural mass matrix.

β: the parameter which define damping matrix.

[K]: structural stiffness matrix.

ωi: is the natural frequency associated to the mode shape “i”.

ζ: damping coefficient

E is earthquake input energy.

Ek is kinetic energy.

Es is reversible strain energy in the elastic range.

Eh is the amount of wasted energy due to inelastic deformation

Ed is the amount of amortized energy by additional damper.

CHAPTER ONE

INTRODUCTION

1.1 Preliminaries

The concept and practical application of the cable-stayed bridge date back to the 1600's, when a Venetian engineer named Verantius built a bridge with several diagonal chain-stays (Kavanagh, 1973). The modern cable-stayed bridge consists of a superstructure of steel or reinforced concrete members supported at one or more points by cables extending from one or more towers. The concept attracted to engineers and builders for many centuries and experimentation and development continued until its modern-day version evolved in 1950 in Germany. The renewal of the cable-stayed system in modern bridge engineering was due to the tendency of bridge engineers in Europe, primarily Germany, to obtain optimum structural performance from material which was in short supply during the post-war years [1].

During the past three decades, cable-stayed bridges have found wide applications all over the world, especially in Western Europe and United States. In particular, the cable-stayed girder type of design is fast gaining popularity among the bridge designers, particularly for medium and long spans.

Cable-stayed bridge stands out as the most recent technological development in bridge construction as demonstrated by several bridges existing all over the world, built of different materials and techniques.

The Stromsund Bridge, which was constructed in Sweden in 1955 with a central span of 183 m is the world's first cable-stayed highway bridge. Subsequently, a number of cable-stayed bridges were constructed all over the world in many countries. The Second Hoogly Bridge over the river Ganga at Howrah is one of the longest bridges in the world with a span of 457.2 m, the Tatara Bridge in Japan being the longest with a span of 890 m. Efforts are on to increase the span further beyond 1000 m. For medium spans of 100 - 300 m, cable-stayed bridges are considered to be the most suitable system [2].

The recent developments in design technology, material quality, and efficient construction techniques in bridge engineering will enable construction of not only longer but also lighter and slender bridges. Thus, very long span slender cable-stayed bridges are being built, and the aim is to further increase the span length and use shallower and moreslender girders for future bridges. To achieve this, accurate procedures need to be developed that can lead to a thorough understanding and a realistic prediction of the structural response to not only wind and earthquake loads but also traffic loads.

Cable stayed bridges have over the last few decades gained recognition as potential super long span bridges due to their higher overall stiffness and aerodynamic stability [3]. The cable-stayed bridges reached a milestone at the beginning of the 21st century when the Russky Bridge (1104 meters) was built in Russia, as shown in Figure (1.1). The Sutong Bridge (1088 meters) in China, and the Stonecutters Bridge (1018 meters) in Hong Kong broke new ground as the first cable-stayed bridges with main spans exceeding 1 000 meter

Figure (1.1) The world’s longest cable-stayed bridge, Russky Bridge (1 104 meters), Russia.[4]

1.2 Cable Stayed Bridge

Cable supported bridges are primarily distinguished by two features: their capability of over bridging long spans and their main structural element, the cable system. Generally, cable stayed bridge consists of the following main structural elements [5]:

- Bridge deck (stiffening girder)
- Cable system (supporting the bridge deck, consisting of either main cables and hangers, or inclined stays)
- Pylons (supporting the cable system)
- Anchorage device (anchoring the tensile forces, either an earth-anchored or a self-anchored system)

The main structural elements, in typical design, for cable-stayed bridges are shown in Figure (1.2)

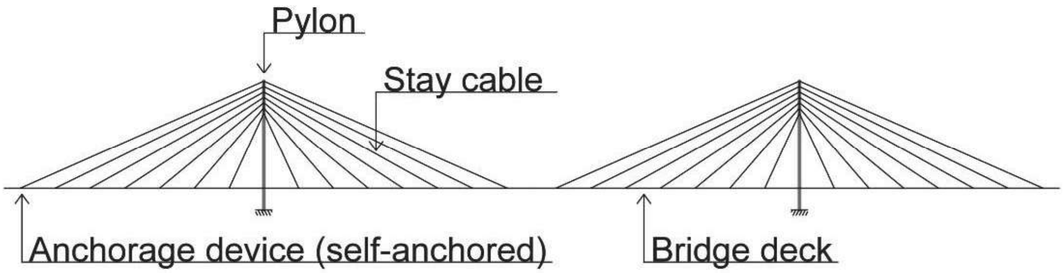


Figure (1.2) The typical design of a cable-stayed bridge and its main structural elements

1.3 Arrangement of Cable Stayed Bridge

The cables can have different arrangements which is divided into three types: harp, fan and radial, as shown in Figure (1.3). The arrangement can have a major effect on the behavior of very long span bridges [6].

1. the harp cable arrangement offers the possibility to start the construction of the girder before the complete pylon is constructed.
2. whit a fan cable arrangement, the cables are working more efficiently in the vertical direction which decreases the horizontal components from the cables and thus the compression in the girder. For longer span bridges compression in the girder can be critical to the design of the bridge and can thus be helped with a fan arrangement.

3. the cables work even more efficiently in the radial arrangement but it can be difficult to design the detail where the cables connect to the Tower.

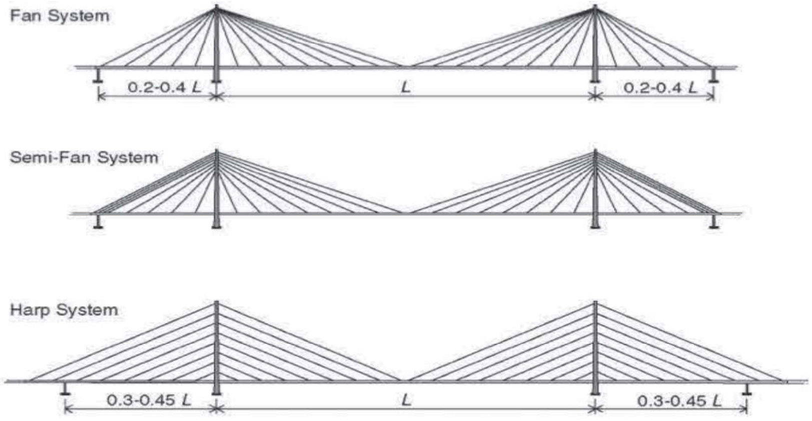


Figure (1.3). Cable system configurations of cable-stayed bridges [3]

1.4 Advantages of Cable-Stayed Bridge

The rapid development of cable-stayed bridge can be partially attributed to its many outstanding characteristics and advantages. Cable-stayed bridge designs are used for intermediate-length spans and filling the gap that exists between the girder type and suspension type bridges. Compared with suspension bridge, cable-stayed bridge has the advantages of ease of construction, lower cost since anchorages are not required and small size of substructures. Furthermore, there are no massive cables, as with suspension bridges, which making cable repair or replacement much easier in cable-stayed bridges. The general trend suggests that cable-stayed bridges with longer span length are becoming possible and economically more advantageous than suspension bridges [7].

1.5 Components of Cable Stayed Bridge

The main cable stayed bridge components can be described as follows:

1.5.1 Cables

The function of the cables is to carry the load of the girder and transfer it to the pylon and to the back stay cable anchorage. The cables are composed of a bundle of tensile elements. The tensile elements are usually cold drawn high performance steel wires. The cable stays can be divided into three different categories based on the tensile elements as follows [8]:

a. Parallel Strand Cable (PSC)

The tensile elements in PSC’s are 7 pre-stressing wires bundled into to a spiral called a “7-wire strand” 15.2 or 15.7mm in dia. Each cable consists of multiple strands where each strand is individually anchored.

The cable category is divided into two types of corrosion protection methods: sheathed or ducted. In the sheathed cables, each 7-wire strand is protected with an individual sheath and filling. Whereas in ducted PSC’s the strands are placed in a duct which protects the strands. The duct can then be filled with a blocking product [9]. PCS’s are manageable, economic and the most common in recent construction, Figure (1.4) show the principle of Sheathed PSC..

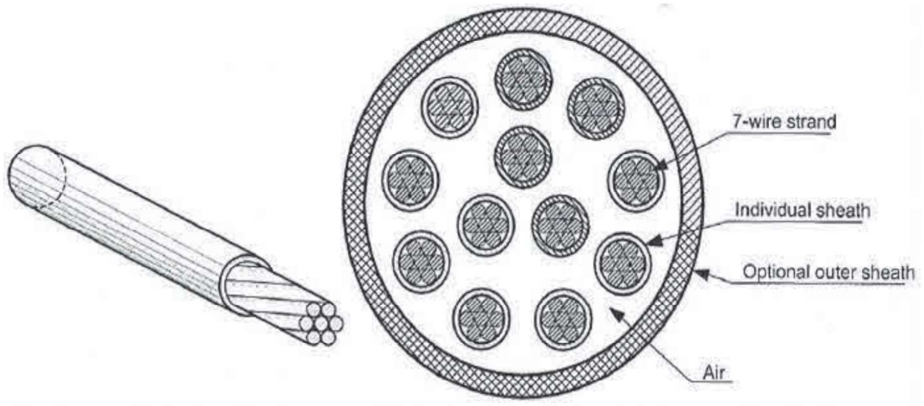


Figure (1-4) Principle of a Sheathed PSC [9]

b. Parallel Wire Cable (PWC)

The tensile element consists of smooth wires 7mm in dia. Bundled into ducts. Each wire is anchored with a machine-formed buttonhead [9]. The cables are prefabricated with exact length and transported in coils to the construction site [6].

c. Multi-Layer Strand (MLS)

The tensile element is round and/or z-shaped wires which are placed in several layers and helically wound round a core wire [9]. These prefabricated cables have been developed to be dense and have a smooth outer surface and protected from corrosion. Since they have a smooth surface the lateral pressure on saddles, sockets and anchorages are less than PWC's and PSC's. The cables can be coiled and reeled for transportation and handling [9], Figure (1.5) show Principle of a MLS.

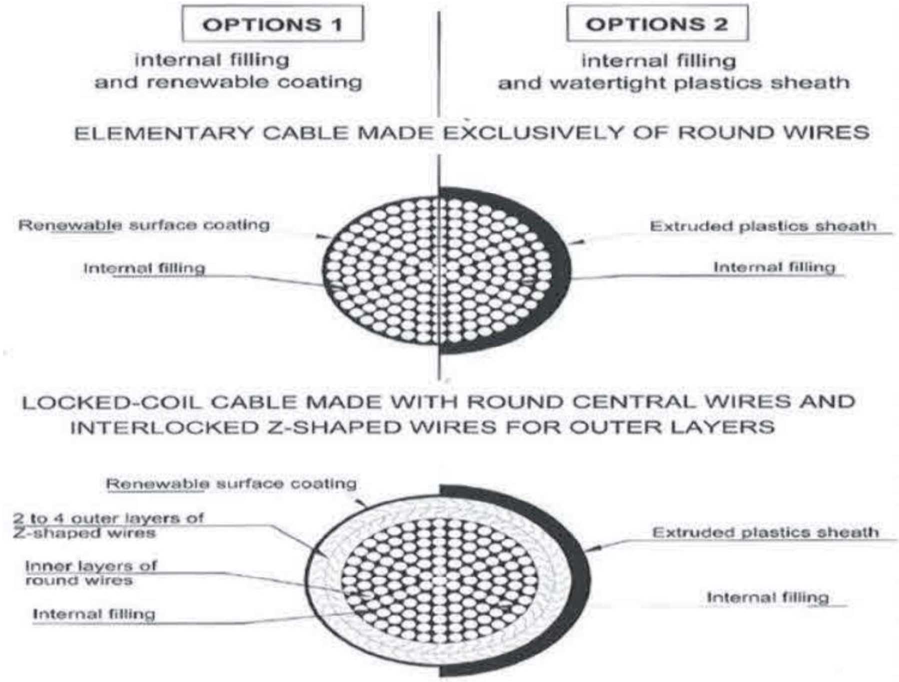


Figure (1.5) Principle of a MLS [9]

1.5.2 Tower

The tower is the most visible element on the cable-stayed bridge, which makes the visual design important. The tower is a compression member. Nowadays most towers are constructed in concrete except special conditions such as areas with seismic hazards. The towers can have different shapes where H, A, inverted Y and diamond shapes are the most common [6]. For spans up to500m freestanding slender towers without transverse bracing is sufficient. Bridges with high level clearances a transverse bracing just below deck level can be required for the horizontal wind loads. An extra transversal bracing in the top of the tower is required for longer bridges. For very long span and strong wind an A or diamond shape is the best choice. The best design for bridges with cables in a single plan is a single slender tower. The tower of a single plan cable-stayed bridge must provide a torsional support of the box girder. Inclined towers are purely aesthetic and have no technical or economic advantages [10], Figure (1.6) show typical tower shapes.

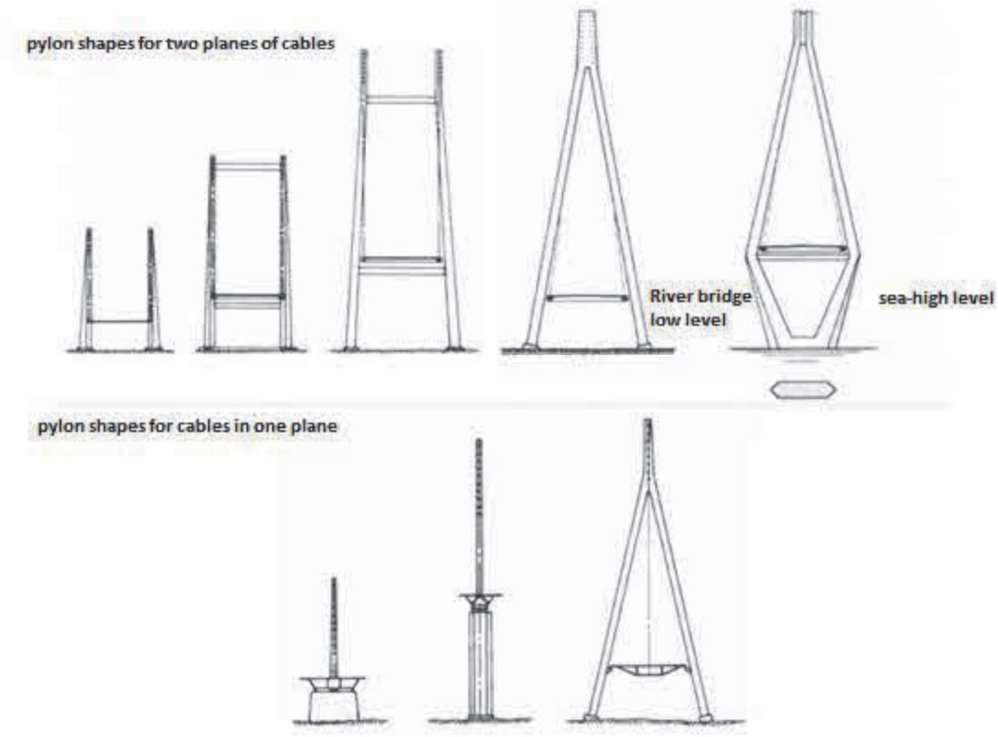
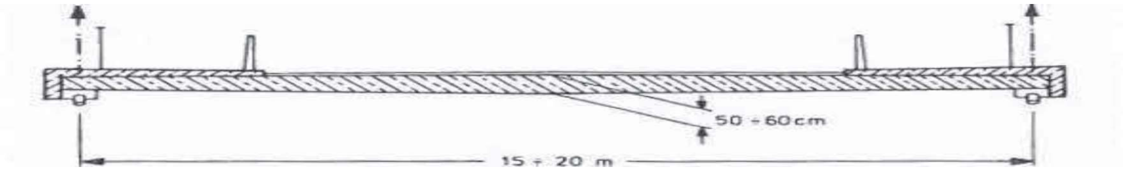


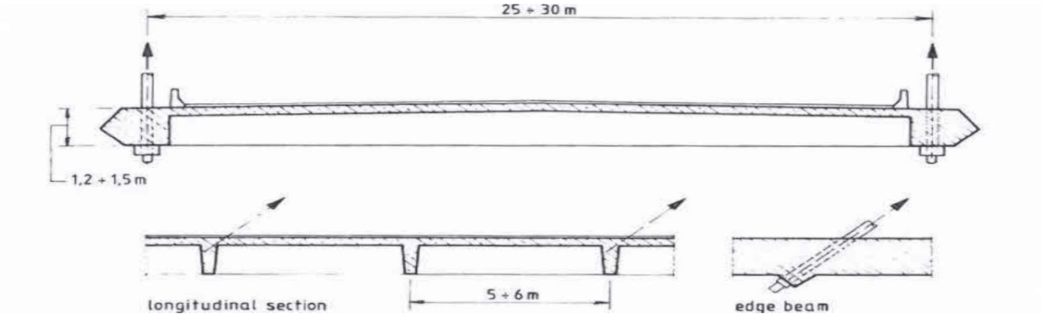
Figure (1.6) Typical Tower Shapes [10]

1.5.3 Girder

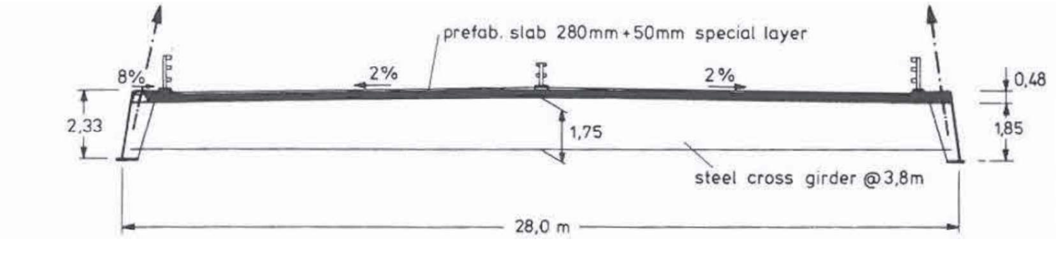
The early cable stayed bridge girders except a few where made of orthotropic steel decks. The Development has since been concrete and composite decks which is more cost effective except for long spans [6]. The cross section of the girder depends on the main type and shape of the bridge. The girder can be designed with a simple cross section where the aerodynamic shape is of less importance to cable stayed bridges than suspension bridges. Railroad bridges require a robust cross section where a large mass benefit the dynamic behavior. For bridges with cables in a single plane, a box section is favored to obtain the required torsional stiffness. The most common and often economical is to have cables in two planes, especially for bridges with longer spans. For smaller bridges with spans up to 200m the best practice is a simple concrete slab without edge beams, as shown in Figure (1.7) (a). A concrete or composite T-beam cross section is the best practice for bridges with spans up to 500m and/or wider than 20 m, as shown in Figure (1.7) (b) and Figure (1.7) (c). The best practice for an even wider bridges and/or longer spans is an orthotropic steel deck. An orthotropic steel deck reduces the self-weight of the structure. From a structural point of view, a cross section with simple edge beams is sufficient. With a box section however, the wind nose reduces the wind load. A box section has a dry inside that is more protected from corrosion and which can reduce the maintenance costs after competition. Two examples are shown in Figure (1.7) (d) and Figure (1.7) (e). The transversal span, the width of the bridge, governs the height of the cross section. Due to the larger normal forces close to the tower, the cross section area often increases towards the tower. Effective measures to increase compression capacity are either by increasing the slab height or constructing the edge beams in concrete. Another alternative is to increase stiffeners [11].



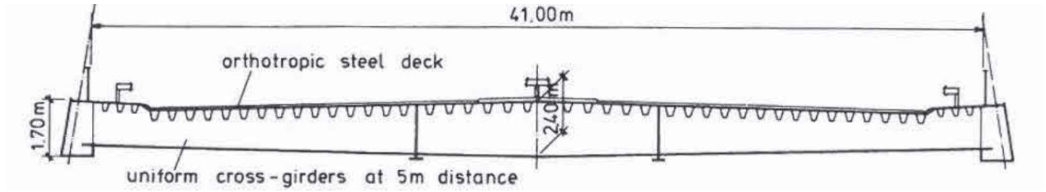
(a) Cross section for spans up to 200m (Diepoldsau bridge)



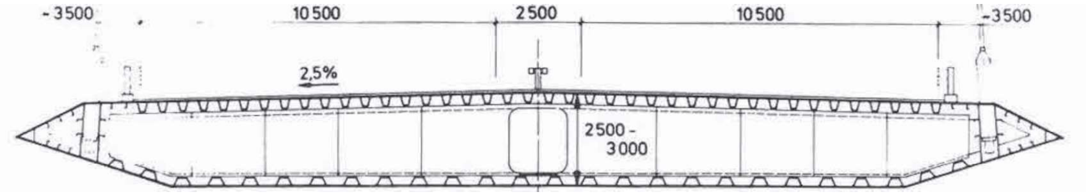
(b) Concrete cross section for spans up to 500m and width > 20m



(c) Composite deck for spans up to 500m and width > 20m (Sunshine Skyway Bridge)



(d) Orthotropic steel deck for spans longer than 500m and wider than 25m



(e) orthotropic steel box suitable for very long spans

Figure (1.7) Typical cross sections of cable stayed bridge girders [10]

1.5.4 Anchorages of the Cables

The most important component is the anchorage of the cables. Most cable stayed bridges need to replace the cables during the lifespan of the bridge. The anchorages must therefore allow for replacement and adjustments [10]. There are bonded and unbounded anchorages. The strands are fixed by removable wedges in unbounded anchorages, and grouted with filling in bounded anchorages. The advantage of unbounded anchorage is that the cable or strand can be more easily replaced. However, a wedge is a delicate structural element and is susceptible to construction deviation which has to be considered in the design. The filling, which distributes the local stresses in each wire/strand in bounded anchorages, improve the anchorages quality for fatigue and overloading [6]. A feasible anchorage placed at the deck structure, consists of a steel pipe attached to the deck. It can either be welded or grouted to the edge beam of the deck depending on the material of the deck. The anchor is often fixed in the correct angle of inclination at the deck and adjustable at the Tower anchor. The steel pipe continues about 1.2m above the road level for protection. At the top is a soft neoprene pad followed by a seal of a rubber sleeve. The soft top stops flexural movements of the cable and damps oscillations [10]. There are three different concepts of anchoring the cables at the Tower: saddle, crisscrossing or dead end. The saddle works similar to a suspension bridge bearing, it is expensive to install and difficult to replace and not recommended for cable-stayed bridges. Crisscrossing and dead-anchor are shown in Figure (1.8). Crisscrossing is simple and economical, although eccentricities should be reduced in order to mitigate torsional moment in the Tower [6, 10]. The dead-end concept eliminates the eccentricities by anchoring the cables inside the tower. The cables can be connected to the walls of the box-shaped pylon cross section. The tower is reinforced with post-tensioning tendons on the sides. The cables can also be anchored to a steel member, a beam or box, inside the pylon which connects the cables. The steel member is connected to the section of the tower by shear studs. This anchorage works like a saddle but the two cables on opposite sides of the tower are independent [6]. In order to tension and adjust the length of the cable there must be sufficient space to place and operate a jack [10].

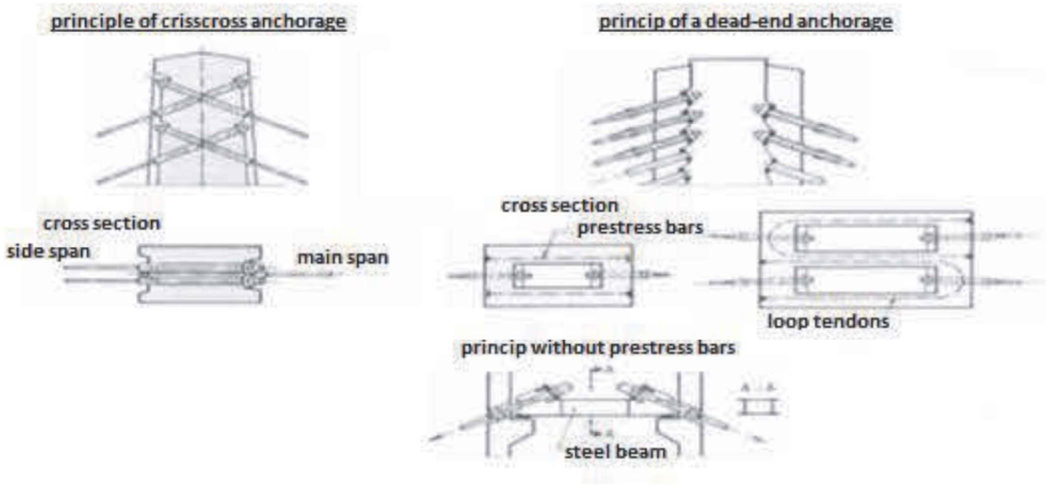


Figure (1.8) Principle of anchorage at Tower [10]

1.6 Seismic Performance of Cable-Stayed Bridge

Earthquakes can have a very serious effect on a bridge. It can cause damage to structural elements, cause vibrations through the bridge, or even lead to a bridge collapse. Understanding the seismic response behavior of cable-stayed bridges is thus important to ensure structural safety and improve future design. Most cable-stayed bridges have a number of long-period modes due to the flexibility of their cable super structure system. However, in a seismic environment, since the largest earthquake spectral accelerations typically occur at relatively short periods, cable stayed bridges with fundamental periods starting from 2.0 seconds tend to have a degree of natural seismic isolation. Thus, a rather favorable combination of structural dynamics and ground motion characteristics often exists for these types of bridges [12]. In the United States, two long-span cable-stayed bridges - the Bill Emersion Bridge in Missouri and the Arthur Ravenel Jr. Bridge in South Carolina are located in seismic active region. The Bill Emerson Bridge, a new Mississippi River crossing in service since December 2003, is located approximately 80 kIn due north of New Madrid, Missouri. The New Madrid area, where the great earthquakes of 1811 and 1812 occurred, is an active seismic region requiring earthquake hazard mitigation programs. Design of the bridge accounted for the possibility of a strong earthquake (magnitude 7.5 or greater) during the design life of the bridge, and as a result was based on design response spectrum anchored to a zero period acceleration (ZPA) of 0.36 g with a 10% probability of being exceeded in 250 years [13]. A state-of-the-art seismic monitoring system with 84 accelerometers was installed to this 1,206-m-Iong (3,956 ft) Bill Emerson Memorial Bridge in 2003 [14].

Unlike ordinary structures, cable-stayed bridges are considered important structures, therefore, required to survive earthquakes of high intensity without collapsing and must also remain operational after the earthquakes as they are required to serve as vital transportation links. Recommended performance-based design earthquake intensities are summarized in Table (1-1). Corresponding to these intensities, the acceptable damage levels are as follows [15]:

- For small earthquakes, bridge should not be damaged
- For moderate earthquakes, the damage level would be small, easy trepair without closure of the bridge, and
- For large earthquakes, significant damages would occur but without bridge collapse or closure for emergency occasions.

Table (1-1) Earthquake intensity [15]

	Earthquake intensity (probability of exceedence in 50 years)		
Bridge significance	**Small**	**Moderate**	**large**
normal	20%	4%	1%
vital	10%	2%	1%

1.7 Damping System

Seismic Dampers are used in place of structural elements, like diagonal braces, for controlling seismic damage in structures. It partly absorbs the seismic energy and reduces the motion of structure.

Dampers are classified based on their performance of friction, metal (flowing), viscous, viscoelastic; shape memory alloys (SMA) and mass dampers. Following are some types of dampers [16]:

- Viscous Dampers (energy is absorbed by silicone-based fluid passing between piston-cylinder arrangement, Figure (1.9) shows Component of viscous dampers.
- Friction Dampers (energy is absorbed by surfaces with friction between them rubbing against each other).
- Yielding Dampers (energy is absorbed by metallic components that yield).

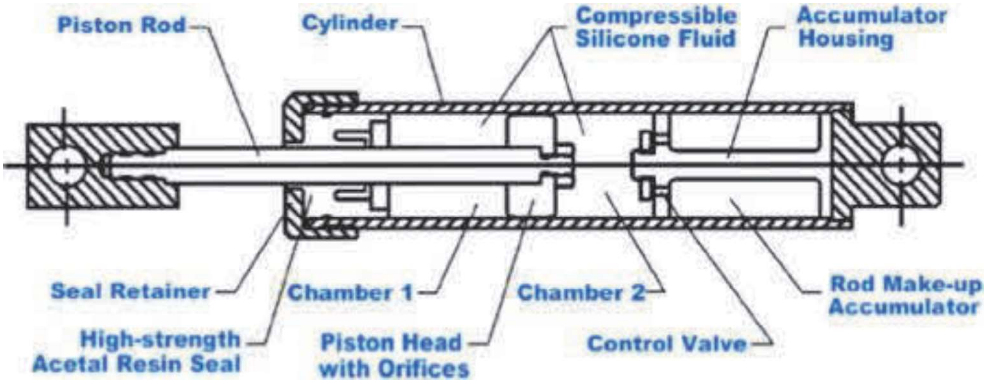


Figure (1.9) Component of viscous dampers [16]

1.8 Scope of Thesis

1.8.1 Research Scope

This thesis presents the results of modeling and analysis of cable-stayed bridge with two H shape tower–the Quancy Bayview Mississibi Bridge located on the USA. Two considerations of three-dimensional finite element models were established for the quaincy Bridge using the ANSYS15.0 software. The first one is a sophisticated finite element model based on the use of link element type to model stays of cable stayed bridge. The other one is based on using multi-beam element type for modeling stays of cable stayed bridge and was used for nonlinear time history analysis of the Quaincy Bridge under earthquakes. Static analysis, free vibration analysis and dynamic analysis of the Bridge were performed in this study. Modeling details as well as the results from the static analysis and dynamic analysis are discussed in this thesis.

1.8.2 Aims of the Study

The main aims of the study are to:

1. study and analyze the process of building finite element models of cable stayed bridges subjected to the effect of earthquake.
2. build a finite element model of a proposed cable stayed bridge containing variable typed, and distribution of dampers along it.
3. analyze the effect of damping coefficient, distribution, direction of proposed dampers located along the bridge, and its ability to withstand dynamic loading.

1.8.3 Organization of Thesis

There are five chapters in this thesis. Chapter 1 provides an introduction to the history and development of cable-stayed bridges as well as the scope of this thesis. Chapter 2 gives a literature survey for seismic analysis of cable stayed bridge. In Chapter 3 both the finite element method as well as modeling details is discussed. Chapter 4 presents the finite element model for dynamic analysis as well as the results from nonlinear time history analysis of the Quanicy Bayview Bridge under earthquakes, Chapter 5 provides conclusions of the research and recommendations for future research.