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ANALYSIS OF PROGRESSIVE COLLAPSE IN CABLE-STAYED BRIDGES DUE TO CABLE FAILURE DURING EARTHQUAKE

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ABSTRACT: Nowadays, Engineers have built some tremendous structures all around the world, as a result, engineers have confronted with several unknown aspects of design and construction methods. Progressive collapse in structures has always been a serious threat, and historically has caused several vast demolitions of man-made structures and lead to damages and loss of lives. One of the causes of these damages is the failure in a number of elements during ultimate events such as 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. Although the structure is designed to resist against the specific earthquake, research reveals that failure of only two elements is capable to cause consequent damages. For this purpose, three earthquake accelerations will be exerted on the structure and simulation of two critical cables failure will be performed simultaneously. The results show that the mentioned situation during Tabas and Loma Prieta earthquakes will lead to progressive collapse, whereas the structure can withstand two cables removal during the Bam earthquake. To avoid this destruction, six base isolations are installed below the structure. Analyses show that this approach can limit the amplitude of axial force below the ultimate strength and progressive collapse can be avoided.

KEYWORDS: Progressive collapse, cable-stayed bridges, time history analysis, base isolation

1 INTRODUCTION

Although many codes and recommendations propose methods for mitigation of progressive collapse in structures, most of them are just in the scope of the buildings. On the other hand, bridges, because of unusual utilization, particularly in times of war, low redundancy of elements and placing in rough conditions are in probable danger of progressive collapse.

One of the most commonly used bridges is the cable-stayed bridge, the application of which has increased dramatically around the world during the last three decades. One of the main causes of the progressive collapse in structures are occurring failure in some elements due to loading beyond the capacity which may be initiated by unpredictable events like terrorist attacks, vehicle collision, etc. But an alternative problem, which can also contribute to consequent destruction, is failure of some critical elements because of fatigue or construction error during ultimate events. As an example, in Tacoma Narrow bridge event, the whole structure was resisting severe winds for about one week, but failure of some cables due to the unknown reason initiated and spread this failure to other cables and entire middle span collapsed. This predefined situation can also occur during sever earthquake which have large vertical earthquake components. This factor has direct influence on the amount of axial loads within the cables and might cause overloading in adjacent elements to ruptured cable/cables.

Most credible codes and recommendations have many instructions to avoid progressive collapse in structures and their recommendations can be outlined in two general divisions: 1)Direct method which includes: specific local resistance method (SLR) and alternative load path method (ALP) and 2)Indirect method which consists of the tie method and compartmentalization. The most presented instructions are the SLR method, where the elements should resist against their predictable forces during their service time. On the other hand, the ALP method is more precise and extensive, but it has lacked usage due to lack of widespread knowledge. Therefore, analysis in this study will be carried out based on this method (ALP). So firstly, according to ALP method, the critical cables will be identified and then, the simulation of this removal during three earthquakes will be presented. At the end, base isolation will be introduced to the structure and behavior of the bridge with and without these instruments will be investigated.

2 BACKGROUND STUDY

Studies in the field of progressive collapse were commenced after destruction of a part of Ronan Point building in London in 1968. Afterward, due to the catastrophic demolition of the World Trade Center in New York in 2001, investigation into the understanding of the progressive collapse phenomena in buildings became highly rapid and significant amount of preventive instructions have been proposed till now. Similarly, in bridges, sudden collapse of the I-35 bridge attracted lots of attention and many studies have been performed. Astaneh et al.(2008) [1] and Hao (2010) [2] introduced some instructions to avoid progressive collapse in bridges. Jiang-gue et al. (2011) studied different evaluations of progressive collapse in cable-stayed bridges[3] and also Starrossek (2010) investigated cable-loss analysis and collapse behavior of cable-stayed bridges.[4]

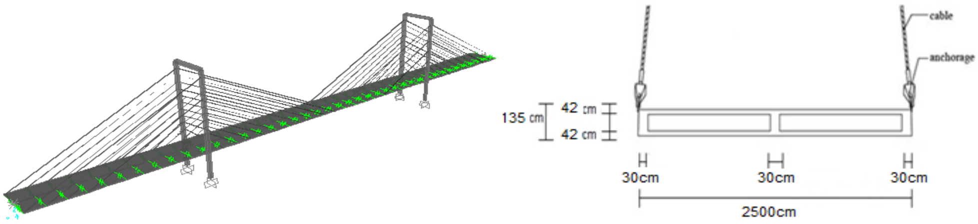
The modern day application of base isolation in structures originated from New Zealand in the 1960s and many important structures have become retrofitted using this method. The mechanism of base isolation is reduction in demand rather than increasing of capacity. As a result, it is introduced as one of the most economic approaches in seismic modification. In this method, the whole structure becomes separated from the ground and thus, transition of seismic load will be dramatically reduced. Shakib and Fouladgar (2003) studied the behavior of an isolated structure which was exposed to a three-dimension earthquake.[5] Mazza et al. (2012) investigated the non-linear response of isolated structure under excitation of near-fault earthquakes.[6]

3 DESCRIPTION OF PARAMETRIC STUDY

3.1 Bridge system

The hypothetical bridge is designed firstly for serviceability and earthquake resistance. In other words, the dimension of elements including cable diameters, dimension of the pylons and so on has been determined before failure analysis according to performance-based design. So all the elements can resist three applied earthquakes within allowable displacements up to IO level in normal condition.

The bridge has two side spans with 100m length and a 200m main span. The deck is a reinforced concrete box with $f'c = 34.42 MPa$, Poison ratio= 0.17 and Young,s modulus=30 MPa. The bridge has four 3m × 3m pylons which are made of the same concrete. The steel that is used for cable elements in the model has $fy = 1320 MPa$,Poison ratio= 0.3 and Young,s modulus= 180 GPa.[3] The cable elements are modeled by truss link which are tension elements with 7 cm diameter, whereas pylons and deck are modeled by frame elements.



(a) (b)

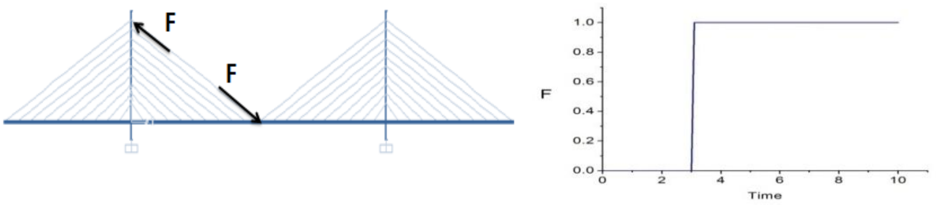
Figure 1. a) Finite element model; b) Dimension of concrete box deck

3.2 Loading

The situation of cable failure during earthquake is not considered in any code, so the following load combination which is suggested by PTI recommendation (2001)[7] and GSA (2003)[8] will be considered during mentioned earthquakes. Load combination:

$$1.0DL+0.75LL+1.0PS+1.0CL \tag{1}$$

where DL and LL are dead and live load in service condition, PS is the prestress force of the cables and CL represents equivalent force to simulate the sudden force of the cable or cables.[3] Dead load is the self weight and calculated automatically by sap2000 and live load is considered 6000 kg/m^2 for four lanes. For the modeling of failure procedure in cables, an equivalent force in the opposite direction of internal force of ruptured cable/cables will be applied to make the total internal force to zero. This force and its variation with respect to time are shown in Figure 2-a and Figure 2-b, respectively. Since it is assumed that the failure happens during the earthquake, so it can be observed that application of this force is at third second in order to model the critical condition. The other times for the cable failure have been examined for each earthquake and prove that the third second is the most critical time for modeling of the failure. In addition, the duration for removal of ruptured cables is considered 0.1 second.



(a) (b)

Figure 2. a) Equivalent force for modeling of failure; b) Variation of equivalent force with respect to time in sap2000

3.2.1 Earthquake loads

In this research, the bridge has been exposed to three specific earthquakes which not only consist of large amount of vertical components, but also their magnitudes and soil characteristics are relatively the same. As redistribution of axial load in adjacent cables and overloading of them are introduced as the main reason of progressive collapse and also the vertical component of the earthquake has the strongest impact on these cable forces, thus, the choice of large vertical component-earthquakes sounds reasonable. Details of these earthquakes have presented in Table 1.

Table 1. Details of chosen earthquakes

Δt	Magnitude	PGA			Year	Station	Name
		z	y	x			
0.02	7.4	0.688	0.852	0.836	1978	Tabas	Tabas
0.005	6.9	0.541	0.433	0.528	1989	Capitola	Loma
0.005	6.6	0.907	0.629	0.807	2003	Bam	Bam

3.3 Non-linearity

As new cable-stayed bridges have larger scales than regular structures, significant displacements occur within the structure during both service condition and earthquakes. As a result, both material and geometrical non-linearity are probable in elements. The geometrical non-linearity has been taken into account by consideration of sagging and P-Delta effects. In order to consider non-linearity in materials, plastic hinge has been introduced to the model. This hinges which are based on their value in FEMA 356[9] is axial hinge for cables and P-M2-M3 for both pylons and the deck. For axial hinge, yield point force according to cable section is 5079.84 KN and ultimate load is 6756.16KN. The stretch rate of cables at yield point is 0.73% and according to FEMA 356 is fourteen times of this value as ultimate. The mentioned hinge is illustrated in Figure 3. P-M2-M3 hinge are introduced to finite element program according to FEMA 356.

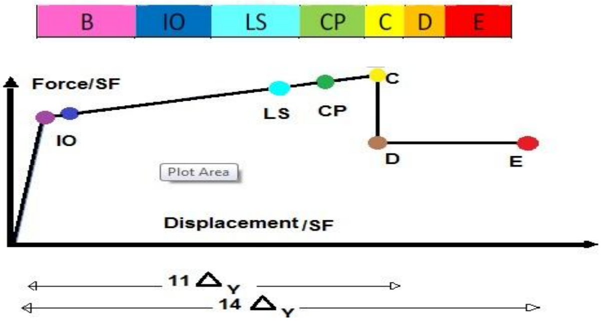


Figure 3. Plastic hinge for axial load

3.4 Base isolation

Today, structures have been retrofitted against earthquake through many different methods, but one of the most common ways is using base isolation. This application, firstly extent the first period of the structure and as a result, the possibility of doubling with period of the earthquake will be drastically reduced and secondly, will absorb the main proportion of earthquake accelerations. Base isolations have different types and the prevalent one is Lead Rubber Bearing (LRB) which is used in this study. The mechanical characteristics are given in Table 2. Four base isolations are located between pylons and ground and two of them are located between deck and support at the end point of the bridge.[10]

Table 2. Mechanical Characteristic of Base Isolation

Z_b	ω_b	Post yield stiffness ratio	Yield Strength(KN)	K_h(KN)	K_v(MN)
0.1	π	0.1	80	800	1500

4 ANALYSIS

Recommendations such as PTI allow designers to carry out an equivalent static procedure in which Dynamic Amplification Factor (D.A.F) is introduced. D.A.F is defined as a dimensionless ratio of maximum dynamic response to maximum static response. However, because of the dynamic nature in failure of cables and magnificent amount of dynamic induced forces including inertia, accurate results can be achieved by the dynamic-based procedure. Among a wide range of dynamic methods, time history analysis has been chosen, as this yield the most precise results.

4.1 Key element

In design procedure, the critical situation is always introduced because if the applied mechanism is able to resist this ultimate condition, it can resist any different situations. Therefore, according to the ALP method, the key element/elements should be removed and consequent effects and secondary situation of stability should be investigated. As it was obtained from another study of the writer, three critical cable failures even in serviceability condition cause progressive collapse within the structure, thus two cables have been candidate for the removal.

By examining through different earthquakes, it turned out that in each quarter of the bridge, each cable which has the largest axial force in service condition, will be the most affected during earthquake and the risk of progressive collapse in its removal is higher than other cable removals. For this purpose, four cables of each quarter and also cable 71 which is, according to the pre-mentioned study, the critical cable in ordinary failure have been selected. These cables are illustrated in Figure 4 with red color.

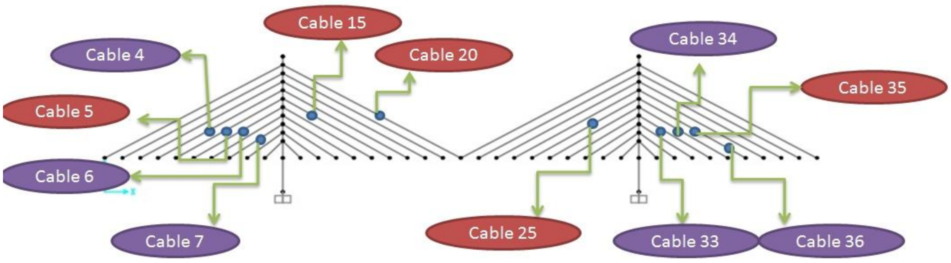


Figure 4. Cables location and their adjacent cables

In local failure, if the other elements are able to endure the secondary increased load, the structure can damp the huge amount of inertia forces, otherwise, progressive collapse will occur. Thereby, the axial force in adjacent cables will be evaluated to understand whether they reach to ultimate load or not.

Figure 5 to 7 show maximum tension forces in adjacent cables of selected one in three different earthquakes to make comparison for introducing of critical cable for each earthquake.

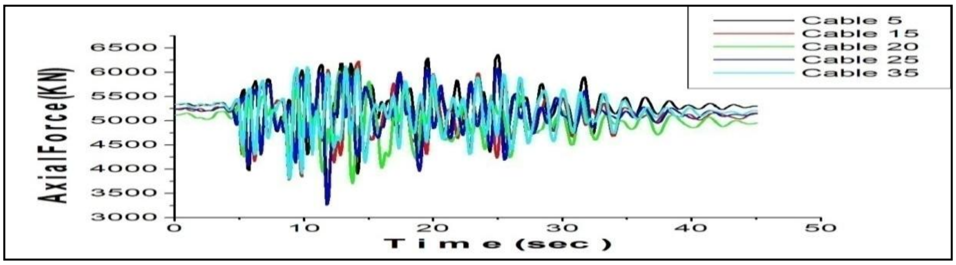


Figure 5. Maximum tension forces in adjacent cables in Tabas

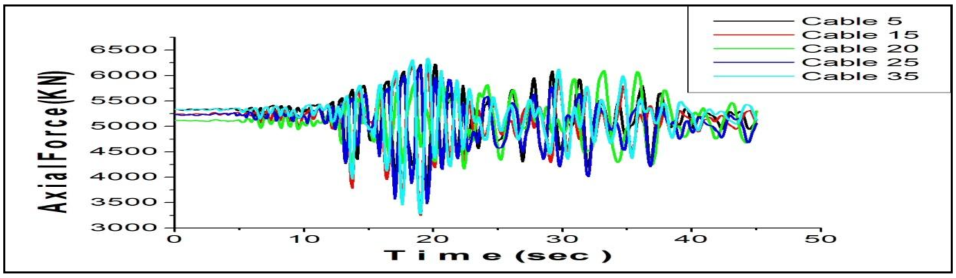


Figure 6. Maximum tension forces in adjacent cables in Loma Prieta

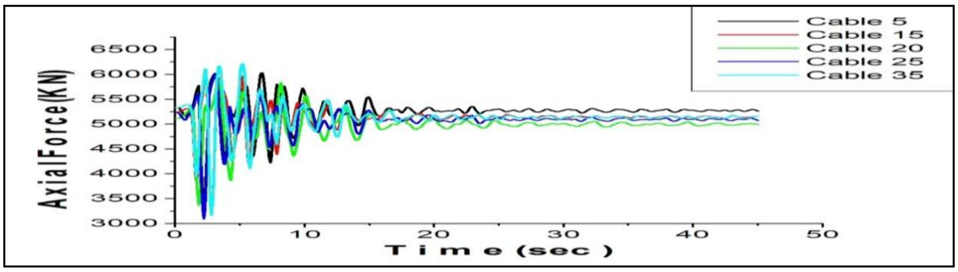


Figure 7. Maximum tension forces in adjacent cables in Bam

According to the above diagrams, in Tabas, cable 5 and in Loma Prieta cable 35 are the critical cable for removal. Therefore, cables 5 and 6 in Tabas and cables 34 and 35 in Loma Prieta will be removed and secondary situation will be evaluated.

5 RESULTS

The critical cables which were identified in section 4.1 will be removed in the third second of earthquake and the secondary equilibrium situation will be discussed. If adjacent cables are able to sustain increased load and also secondary displacements are in acceptable range, the occurrence of progressive collapse will be avoided. Figure 8 to 10 show that in the hypothetical bridge, two critical cables removal during Tabas and Loma Prieta lead to progressive collapse and the entire middle span are destroyed, while this condition during Bam will not cause any damage and other cables can sustain the increased load.

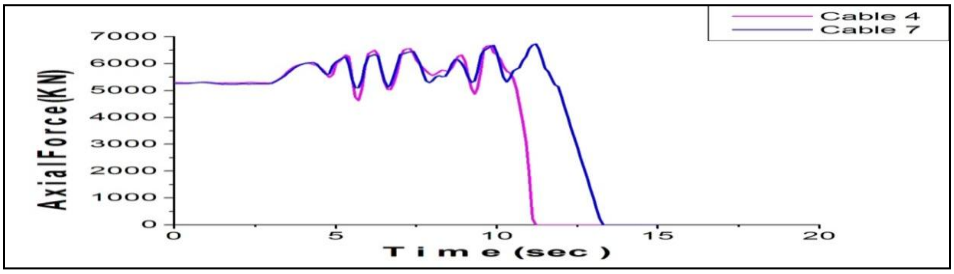


Figure 8. Variation of maximum tension forces in adjacent cables after removal in Tabas

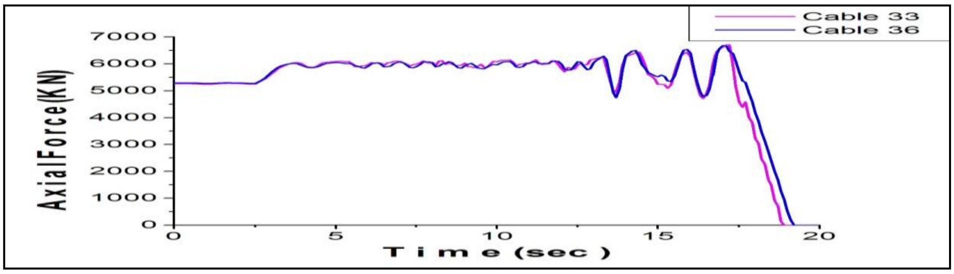


Figure 9. Variation of maximum tension forces in adjacent cables after removal in Loma Prieta

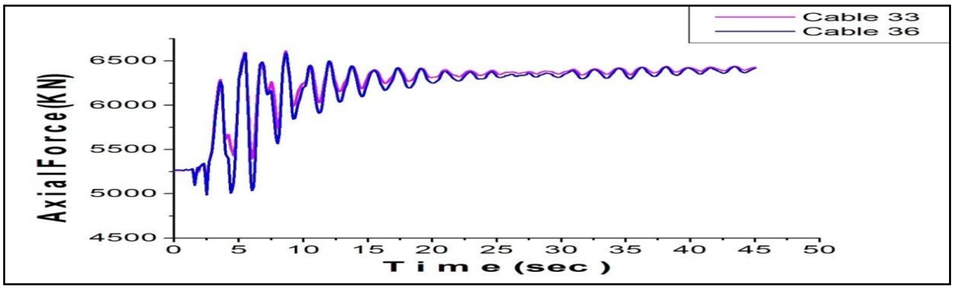


Figure 10. Variation of maximum tension forces in adjacent cables after removal in Bam

In order to prevent this mechanism during Tabas and Loma Prieta, installation of base isolation beneath the structure were suggested. For this purpose, Four base isolations were situated below four pylons and two others are installed between the deck at the two ends and their relevant supports.

The analysis shows that with decreasing in amplitude of axial force vibration, reaching this value to the ultimate limit (6756KN) will be avoided. Figure 11 and 12 show maximum tension force of adjacent cables during Tabas and Loma Prieta in the presence of base isolation. It can be observed that the effect of two critical cables failure during the most critical earthquakes for progressive collapse phenomena can be eliminated in a few seconds by the use of base isolation, therefore, all other kinds of such incidents will lead to the obtained result. As the utilization of base isolation have many benefits including decline in the amount of base shear, decrease in horizontal displacements and leading to economic design of structures, Therefore the usage of this equipment is supported not only for mitigation the risk of progressive collapse within structures, but also for a perfect and flawless design.

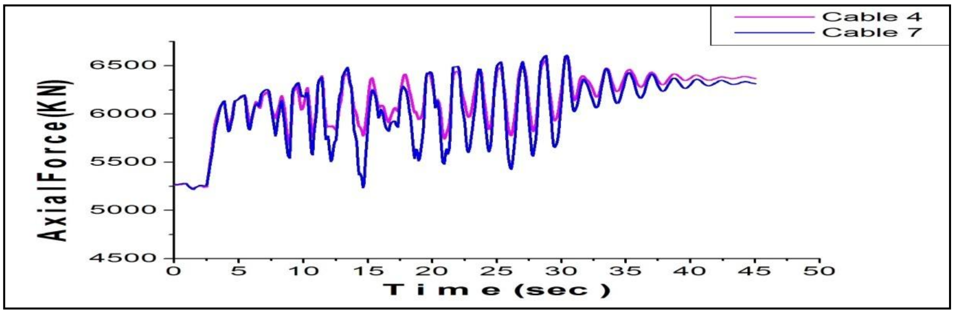


Figure 11. Variation of maximum tension forces in adjacent cables after removal in Tabas in the presence of base isolation

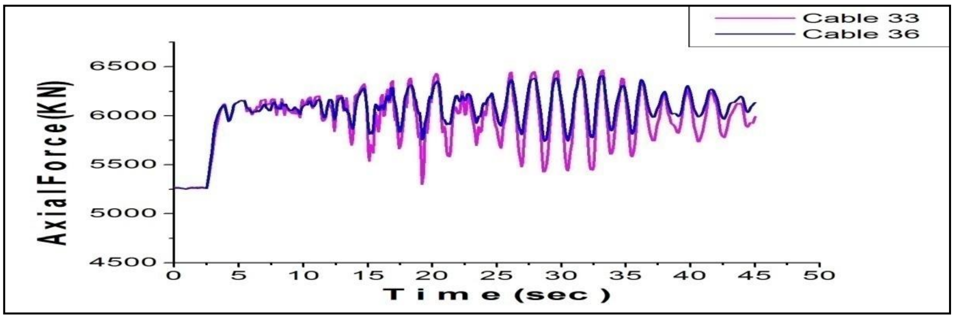


Figure 12. Variation of maximum tension forces in adjacent cables after removal in Loma Prieta in the presence of base isolation

6 CONCLUSION

- The critical cable of the bridge during different earthquakes can vary. Determination of this cable is based on ALP method and comparison of maximum force for adjacent cables. In all earthquakes, the critical cables are the middle ones which have the largest axial force in service condition. Therefore it is essential to pay much more attention to these cables in design procedure.
- Unlike service condition in which three cables removal are needed to trigger progressive collapse, but during Tabas and Bam only two cables rupture lead to consequent failures of other cables. Since fatigue, corrosion and other such problems (due to rough surroundings) often occur, the degraded condition of the most cable-stayed bridges are highly likely, thus, destruction of these structures due to cable failure are imminent.

Progressive collapse which happens by failure of two critical cables during an earthquake can be avoided by the use of base isolation. This application will limit the amplitude of axial force vibration and prevent reaching ultimate force. As the most critical situation was studied in this experiment, all other situations yield the same results.

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