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A study on progressive collapse response of cable-stayed bridges for deflection and axial force in cables

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Abstract – *Stays of cable stayed bridges have potential to loss their support initially by extreme loadings such as earthquake, thunder strike, vehicle impact and wind. The sudden loss of cable(s) provides unpredictable stress redistribution on the deck towers, as well as the large deflection of the entire bridge. Considering such a sudden loss of cable in the design of a cable-stayed bridge is essential. Although cable loss scenarios are associated with material as well as geometrical nonlinearities, in design of cable-stayed bridges, such an extreme loading scenario is analysed typically by using linear elastic models. In this paper, a linear elastic 2D and a fully nonlinear 3D finite element model of an idealised steel cable-stayed bridge are developed and analysed to determine the effect of sudden loss of cable on the progressive collapse of the bridge at global and local stress levels. A parametric dynamic analysis for the bridge model with different cable loss scenarios under symmetrical loading condition is investigated. The deflection which is equal in both the spans of the bridge with healthy bridge condition changes into major deflection in one span after loss of cable in other span. Also the axial force in cables unevenly distributed with loss of any cable which enhance risk of collapse with moving loads.*

Key Words*: *Cable-stayed Bridge; non-linearity; progressive collapse

1. INTRODUCTION

Stays of cable-stayed bridges are critical structural elements which are subjected to corrosion, abrasion, wind, vehicle impact and malicious actions and these extreme scenarios may lead to severe damage and loss of cable(s). Such cable loss scenarios would lead to high impulsive dynamic loads in the structure that can potentially trigger a "zipper-type" progressive collapse of the entire bridge. Accordingly, cable-stayed bridges should be designed for potential cable loss scenarios as recommended by the PTI guidelines (2007).

Progressive collapse has gained importance in structural design. Progressive collapse is triggered by sudden loss of one or more critical structural components that typically take place over a short period of time due to high strain rate loadings such as blast or impact. Similarly, collapse of the cabled bridge structures can be triggered by loss of cables which may occur due to several reasons, such as earthquake or wind induced vibrations (e.g. Tacoma narrow bridge) and traffic loads. The potential progressive collapses assessment of structures can be carried out either statically or dynamically. However, the non-linear dynamic models are possibly the most accurate option for collapse analysis of structures. Apart from dynamic analysis, the equivalent static analysis with dynamic amplification factor (DAF) has also been successfully used for potential progressive collapse assessment of structures. The typical DAF used in conjunction with equivalent static analysis is DAF = 2.0. In addition, using the results of dynamic FE analysis, the back stays connected around pin-support and cables connected to the mid-span have been identified as the most critical cables which their loss can significantly affect the entire bridge.

In this paper, a hypothetical cable stayed bridge with a concrete box deck is analysed and designed according to Indian standards IS800:2007, IS1915:1961, IRC 112: (Code of Practice for Concrete Road Bridges), IRC:006, IRC:078 requirements. Using SAP2000 v.17 software, 2D and 3D FE models of the bridge are developed and analysed under gravity loads and subject to different cable loss scenarios. Using the developed FE models, a comprehensive parametric study is carried out and the effects of location, number and pattern of lost cables on the potential collapse response of the bridge are studied. Furthermore, the two models of health bridge without any cable loss and a model with loss of cable(s) is compared for deflection and forces in cable parameters and the significance of material and geometrical nonlinearities on the potential collapse response of the considered cable stayed bridge is investigated as well.

1.1 SCOPE AND OBJECTIVE

Following are the main objective of the present study:

- To study the behavior of cable stayed bridges for sudden loading such as blast loading, earthquake etc with progressive collapse.
- To study its behavior for maximum deflection and increase in axial force in other cables and collapse.

1.2 REVIEW OF LITERARURE

B. Samali, Y. Aoki, A. Saleh & H. Valipour2015 (1) In this paper detailed 3D finite element models of a hypothetical cable-stayed bridge is developed and analyzed with material and geometrical non-linearities included. A parametric study is undertaken and effect of cable loss scenarios (symmetric and unsymmetric), deck configurations (steel box girder and open orthotropic deck) and number of lost cables on the progressive collapse response of the bridge is investigated. With regard to the results of parametric study, it is concluded that the deck configuration has a minor influence on the progressive collapse response of cable-stayed bridges. Also, it is shown that localized yielding of steel may occur following loss of more than one cable, however, such localized plastic strains cannot trigger the progressive collapse of the entire bridge. During cable loss scenarios, the reduction in post-tensioning stress and subsequently stiffness of the remaining cables (reflected in Ernst's modulus) is found to be around 10% that warrants effect of geometrical non-linearities within the cables being considered.

Yukari Aoki, H. Valipour, B. Samali and A. Saleh 2012(2) In this paper, a finite element (FE) model for a cable-stayed bridge designed according to Australian standards is developed and analysed statically and dynamically with and without geometrical nonlinearities. The dynamic amplification factor (DAF) and demand-to-capacity ratio (DCR) in different structural components including cables, towers and the deck are calculated and it is shown that DCR usually remains below one (no material nonlinearity occurs) in the scenarios studied for the bridge under investigation, however, DAF can take values larger than two. Moreover, effects of location, duration and number of cable(s) loss as well as effect of damping level on the progressive collapse resistance of the bridge are studied and importance of each factor on the potential progressive collapse response of the bridge is investigated.

M. Wolff , U. Starossek 2010(3) This paper shows the possibilities and limits of such an approach for cable-stayed bridges. Furthermore, collapse analyses of a cable-stayed bridge are conducted. With this, structural properties are identified which are responsible for collapse propagation. The prevailing collapse type is described and recommendations for the design of robust cable-stayed bridges are given.

C.M. Mozos, A.C. Aparicio 2010 (4) The present paper deals with the dynamic response of cable stayed bridges to the sudden loss of a stay. Its objectives are to quantify the relative importance of the accidental ultimate limit state of failure of a stay in the design of the bridge, and to determine the safety level provided by the simplified procedure of using a static analysis with a D.A.F. of 2.0. For this purpose, a parametric study has been carried out. In this study, ten cable stayed bridges have been analyzed and the effect of characteristics such as the layout of the stays, either fan or harp pattern, the number of planes of stays and the stiffness of the deck have been studied. First, this paper describes the geometry and materials of the cable stayed bridges studied, the numerical models and the basis of the static and dynamic analysis developed. Next, the results related to the deck cross sections are presented and discussed. Finally, some conclusions related to the design and analysis of the cable stayed bridges are provided. A second companion paper (i.e. Part II) is focused on the response of the pylons and the stays.

G. E. Valdebenito, A.C. Aparicio and J.J. Alvarez 2009(5) This paper presents a numerical comparative seismic analysis of the response of cable-stayed bridges for different stay cable arrangements, in which the main objective is to propose the best structural configurations from a seismic point of view. Firstly, eight symmetric concrete theoretical cable-stayed bridge models based on the well-known Walther's Bridges are defined considering variations of the cable arrangement, deck level and stay spacing. As a starting point, a nonlinear static analysis is performed for all the cases in order to compute the main geometric nonlinearities involved with the overall change in the bridge geometry, nonlinear cable sag effect and axial force-bending moment interaction in towers and girders. After that, the dynamic characterization of the models is carried out by means of a modal analysis considering the modified stiffness matrix obtained from the nonlinear static analysis.

Wenliang Qiu, Meng Jiang, and Cailiang Huang 2014(6) Using nonlinear static and dynamic analysis methods and adopting 3D finite element model, the responses of an actual self-anchored suspension bridge to sudden breakage of hangers are studied in this paper. The results show that the sudden breakage of a hanger causes violent vibration and large changes in internal forces of the bridge. Based on the actual bridge, the influences of some factors including flexural stiffness of girder, torsion stiffness of girder, flexural stiffness of main cable, weight of girder, weight of main cable, span to sag ratio of main cable, distance of hangers, span length, and breakage time of hanger on the dynamic responses are studied in detail, and the influencing extent of the factors is presented.

M. Wolff and U. Starossek 2010(7) The general aim in designing structures, where the consequences of a collapse are high, must be collapse resistance. This means that no structural damage should develop that is disproportionate to the triggering event. Generally, structures can be made collapse resistant by ensuring a high level of safety against local failure or by designing for the failure of elements and thus increasing the robustness. Increasing the robustness of cable-stayed bridge s is achieved by means of designing for the loss of cables. For this, quasi-static analyses using a dynamic amplification factor are recommended by guidelines. This paper shows the possibilities and limits of such an approach for cable-stayed bridges. Furthermore, collapse analyses of a cable-stayed bridge are conducted. With this, structural properties are identified which are responsible for collapse propagation. The prevailing collapse type is described and recommendations for the design of robust cable-stayed bridges are given.

Uwe Starossek, 2006(8) It is shown that current design methods are inadequate to prevent progressive collapse. Definitions for the terms collapse resistance and robustness are proposed. An approach for designing against progressive collapse is suggested and a set of corresponding design criteria is presented. These include requirements, design objectives, design strategies, and verification procedures. In addition to the better-known design methods providing specific local resistance or alternate load paths, an approach based on isolation by compartmentalization is presented and discussed. It is found that the terms continuity, redundancy, and robustness should be carefully distinguished. The general concepts and findings presented here are applied to bridges.

Yukari Aoki, Hamid Valipour, Bijan Samali, Ali Saleh 2014(9) In design of cable-stayed bridges, sudden loss of cables are usually associated with material as well as geometrical nonlinearities which may trigger progressive collapse of the entire bridge. Accordingly, the possible reasons of loss of cable would be the blast loadings, which is one of the concerned situations after 911 terrorist attacks. In this paper, detailed 3D finite element models of a hypothetical cable-stayed bridge deck is developed and analysed with material and geometrical nonlinearities included. A parametric study is undertaken to investigate the effect of blast loadings with different material properties, section properties and different amount of explosive materials, to determine damaged area, number of loss of shell elements as well as cable elements due to explosion. With regard to the results of FE analysis, it is concluded that the maximum 3 cables would be lost by the large amount of TNT equivalent material due to damage of the anchorage zone.

2. Methodology

a) A thorough literature review to understand the basic concept of the topic like seismic evaluation of bridge structures, dynamic amplification factor, progressive collapse and nonlinear analysis by referring books, technical papers or research papers.
b) Data collection.
c) Progressive collapse with successive cable loss.
d) Modeling the cable stayed bridge model 200meters length, 6 meters wide with two spans and one pylon 60 m high at center using SAP2000 v.17.
e) Carry out analysis with bridge construction scheduler which automatically takes all the loadings with construction stages. Cross verified with another model giving dead and moving loads. And check in results for deflection and axial forces in cables. This is healthy bridge model (M1).
f) Preparing another model with loss of one or more cable(s) having maximum axial force before and analysed, and again check for deflection and axial forces in results. (M2).
g) Both the models M1 and M2 compared and prepared conclusions.

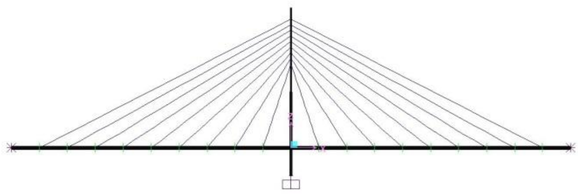

Fig -1: 2D view of the M1 model

3. Theoretical Content

Cable-stayed bridges as well as suspension bridges can be exposed to severe loading conditions and might be damaged as a result. One of the most notable bridge collapses has been the spectacular collapse of the Tacoma Narrows Bridge in the United States due to aerodynamic instability caused by wind loads. The bridge's main span collapsed into the Tacoma Narrow on 7th November 1940, four months after it was opened. The main reason for the collapse of Tacoma Narrows Bridge was wind-induced resonance and the ratio between the span and the deck depth as well as very low torsional stiffness of the deck. In Tacoma bridge case, the first stay snapped by excessive wind-induced distortion of the bridge deck, the entire girder peeled off from the stays and suspension cable(s). Such cable loss scenarios can/may lead to high impulsive dynamic loads in the structure that can potentially trigger a "zipper-type" progressive collapse of the entire bridge (Starossek, 2011).

In this paper, a hypothetical cable stayed bridge with a concrete box deck is analysed and designed according to Indian standards IS800:2007, IS1915:1961, IRC 112: (Code of Practice for Concrete Road Bridges), IRC:006, IRC:078 requirements. Using SAP2000 v.17 software, 2D and 3D FE models of the bridge are developed and analysed under gravity loads and subject to different cable loss scenarios. Using the developed FE models, a comprehensive parametric study is carried out and the effects of location, number and pattern of lost cables on the potential collapse response of the bridge are studied. Furthermore, the two models of health bridge without any cable loss and a model with loss of cable(s) is compared for deflection and forces in cable parameters and the significance of material and geometrical nonlinearities on the potential collapse response of the considered cable stayed bridge is investigated as well.

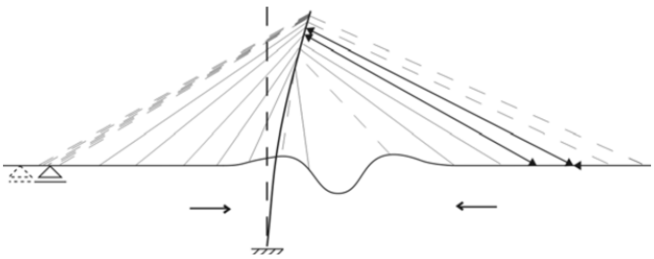

Fig -2: Pylon pull after cable loss

4. CONCLUSIONS

- The result of the present study shows that with the loss of 2 numbers of cables, the deflection in deck at that particular point is noted to be increased simultaneously the stresses in remaining cables increases which may increase the possibility of bending of pylon to one side and collapse of span opposite to loss of cable.
- The configuration of the deck has minor influence on the dynamic response of the bridge following loss of one or two cables, while box girders exhibited lower torsional effects.
- The tensile stresses in cables, following symmetrical or unsymmetrical cable loss and loading scenarios remained well below the breakage stress of the cables, and accordingly, for the cable stayed bridge considered in this study, loss of one or even two cables did not trigger a zipper-type progressive collapse
- In the analysed bridge, material nonlinearity (yielding of steel) and buckling of steel plates did not occur at global as well as local levels. Accordingly, it was concluded that the zipper-type collapse triggered by formation of plastic hinges is unlikely to happen in the cable stayed bridges that have lost two cables or less.

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