INNOVATIVE DESIGN AND TESTING OF A SEISMIC RETROFITTED STEEL DECK TRUSS BRIDGE

Dr. Majid Sarraf, P.E., P.Eng

Dr. Michel Bruneau, P.Eng

Dr. Sarraf is a Senior Project Engineer and Seismic Specialist at Imbsen and Associates Inc. in Sacramento, CA. He is a lead project engineer, seismic analyst and retrofit designer of a number of major bridge projects, including a section of a very complex detour bridge structure of San Francisco-Oakland Bay Bridge.

Dr. Bruneau is the director of Multi-Disciplinary Center for Earthquake Engineering Research and a professor of Civil Engineering and State University of New York at Buffalo. He is a lead investigator of various research projects in the area of earthquake-resistant design of building and bridge structures, seismic evaluation and retrofit of bridges and behavior of steel and composite material.

ABSTRACT

Often seismic retrofit strategies considered for log and medium span steel truss bridges include seismic isolation, strengthening of substructure and superstructure structural members, or the combination of these. Use of ductile steel components as fusing mechanism used in the superstructure was developed by the authors and proved to be an innovative and alternative to more traditional retrofit strategies. This is achieved by conversion of the existing non-ductile end cross-frame and the last lower lateral bracing members to ductile steel frames, which can yield and act as fuses to protect both superstructure and substructure of a bridge. This retrofit is particularly advantageous to other retrofit measures, as it requires minimum retrofit to the structure with no interruption to the traffic on a seismically deficient bridge. Steel ductile retrofits using eccentrically braced frame, vertical shear link, and TADAS system were designed, and incorporated into ductile framing using performance based design procedures.

To validate the proposed ductile retrofit through testing, a 27-ft long, 3-dimensional model of a steel deck-truss bridge was designed, detailed and fabricated at the University of Ottawa, Canada. The bridge was tested using pseudo-dynamic algorithm in its as-built, retrofitted conditions to evaluate its seismic response to El Centro Earthquake. Both eccentrically braced frames and vertical shear link configurations were designed and replaced existing cross-bracings. Measurements of deformations in both ductile devices indicated considerable cyclic ductility and energy dissipation when the bridge was subjected to El Centro earthquake scaled to 0.8 g. No other bridge members failed or suffered damage under such a high seismic loads. This paper briefly describes the proposed design procedure for ductile design of retrofits, retrofit details and features of the test bridge. Pseudo-dynamic test results and hystresis of ductile steel retrofits are presented. The overall performance of the bridge model as well as ductile retrofits are compared.

INTRODUCTION

The collapse of a 288-ft span of San Francisco-Oakland Bay Bridge during Loma Prieta Earthquake of 1989 was a wake-up call to practising engineers and bridge owners to rigorously consider seismic evaluation of steel trusses. Although existing truss bridges are typically lighter than comparable spans of concrete bridges, they could suffer damage. Indeed, seismic evaluations conducted on many existing deck truss bridges in the recent years have revealed that they could suffer damage in the event of major earthquakes (Imbsen and Liu 1993, Matson and Buckland 1995, Astaneh-Asl, et al. 1994, Housner and Thiel, 1995, and Bruneau et al. 1996). Although the degree of vulnerability and extent of potential damage in major bridges could vary, no significant damage is tolerable for functional level earthquake, and only repairable damage with limited closure is acceptable for safety evaluation earthquakes.

In the case of the deck-truss bridges, deck is supported over trusses. Lateral inertia forces of the earthquake applied at the deck level is indirectly transferred to the bridge supports at the end of the lower chords, imposing forces on the entire superstructure members to carry these forces. Typically, existing lateral load resisting members and their connections are not ductile and, therefore could suffer damage in the event of a major earthquake. Particularly, lateral bracings and end and intermediate cross-frames, in older truss bridges which were typically designed for wind forces or stability during construction, cannot be expected to withstand the severe cyclic inelastic deformations expected to develop during large earthquakes.

In addition to vulnerability of superstructure, these bridges are often found to be supported on unreinforced masonry or concrete substructures, which have a very non-ductile deformation characteristic. Thus, the substructure of such a bridges would also be at high risk of damage during a major seismic event. Alternative seismic retrofits, which are commonly used, are: Strengthening many non-ductile bracing and their connections, as well as strengthening the substructure, or using seismic isolation bearings. These alternatives are viable but could be costly and difficult to implement.

STEEL DUCTILE RETROFIT STRATEGY

The proposed ductile retrofit requires conversion of each end cross-frame into a ductile panels having a specially designed yielding device (i.e. a structural fuse), and conversion of the last lower end panel near each support into a similar ductile panel. In addition, stiffening of the top lateral bracing system is also needed. This stiffening has two benefits: It reduces the forces imposed on the interior cross-frames resulted from differential lateral displacement between top and bottom lateral system; second, it increases the share of the total lateral load transferred through end and top lateral system. This can be easily achieved by providing composite action between the concrete deck and the top chord system and eliminating discontinuity in the deck system.

A detailed design procedure for such ductile retrofits are described in Sarraf, 1998(a). This retrofit design is based on two main criteria: strength and stiffness. The yield strength of the ductile panels are selected to be lower than the capacity of the substructure and other superstructure to protect these components. The stiffness criteria established is based on the ductility capacity and drift limits of the superstructure. On the other hand, a very flexible device would result in large lateral displacements of superstructure and possible damage in the adjacent non-ductile members and their joints, on the other hand a very stiff device could have a substantial local ductility demand exceeding their ductility. Using the above criteria and an optimization process the end bracing and ductile components of an eccentrically braced frame and vertical shear links were designed for a 270-ft span deck-truss bridge (Sarraf, 1998.b). These ductile devices were also designed and detailed to be used as retrofits for the scale model of a deck-truss bridge.

Analytical models of the prototype truss bridge were generated using DRAIN-3DX program, in which nonlinear behavior of the ductile shear links were modeled. A series of nonlinear time-history analyses were performed for 6 different earthquakes scaled to 0.53 g (El-Centro 1940, Northridge 1994, San Fernando, 1971, at Pacoma Dam, Loma Prieta, 1989, Olympia 1949 and Taft 1952). The result of these analyses indicated that other than ductile components which yield and dissipate the induced seismic energy, no other superstructure members suffer damage. The force response of the substructure does not exceed its capacity limit, and the average global ductility for all 6 earthquakes does not exceed the global ductility capacity of ductile frames qualified for reduction factor of *R=10* in accordance with UBC. Also, the distortion angle of a shear link as required by AISC-LRFD does not exceed the 9% rotation limit.

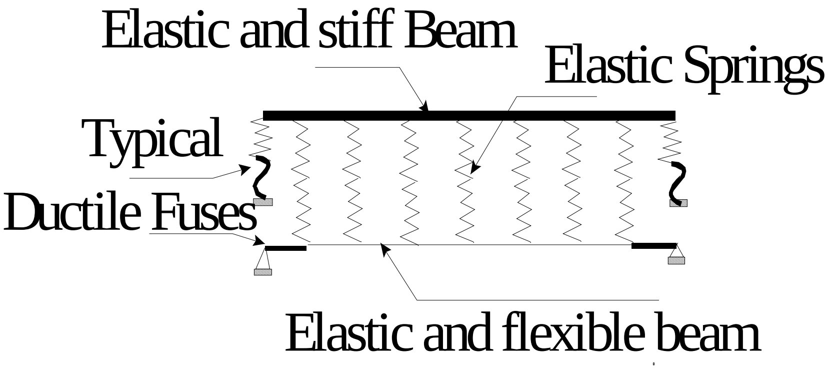

Figure 1(a). *Beam analogy of ductile retrofit system*

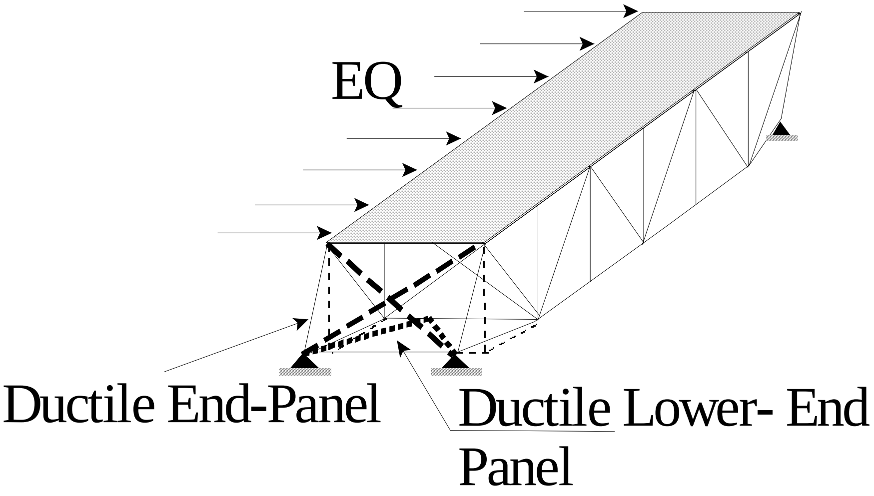

Figure 1(b). *Steel ductile retrofit in a deck-truss bridge*

TESTING STEEL DUCTILE RETROFITS

A 27-ft span steel deck-truss model was designed and constructed in the structures laboratory of the University of the Ottawa. It is 27-ft long, 4-ft wide and 4-ft high. Series of pseudo dynamic tests were conducted to observe the actual performance of the retrofits and confirm that other than ductile retrofit devices no damage occurs in other members of the superstructure. An innov ative loading technique was devised and used to convert a point load applied by one actuator to a distributed inertial force at the deck level. One hydraulic jack positioned vertically is used to apply the gravity loads. Figure 2 shows a general view of the completed bridge model as-retrofitted and the test set-up components.

A specially designed ductile retrofit panel including stiff bracing members and ductile links was used to replace the existing end and lower end panel conventional cross-bracing. Figure 5 shows the details of the vertical link retrofit for the end-panel. A 225-mm thick and 1100 mm wide reinforced concrete deck was cast in place. Shear studs were designed such that they could resist both forces in-plane shear force caused by both seismic loads as well as gravity loads. The end panel and lower end panel connections were high-strength bolts with minimum hole clearance which were designed to have a negligible slip. Therefore, the complete retrofit member assembly could be dismembered after testing the retrofits and the new ductile retrofit assembly would be replaced and tested. Figure 6 shows the end-panel retrofit using vertical shear link.

PERFORMANCE TESTS OF DUCTILE RETROFIT

Initial free vibration tests and cyclic loading tests were performed to determine stiffness and strength characteristic of retrofitted bridge. Subsequently, cyclic tests were performed which resulted in measured yield strength of 450 kN in the EBF retrofit, and 400 kN in VSL specimen. Yielding of both end and lower-end panel devices were detected. The measured yield strength of the retrofits were greater than predicted load of 300 kN due to a number of factors such as: actual yield strength of the steel material, resistance contribution of other components such as connections of the end panel and the last side diagonal members of the truss, as well as a small horizontal component of the applied vertical load. However, despite the additional strength in the devices, no sign of yielding or buckling of the other members of the truss was observed.

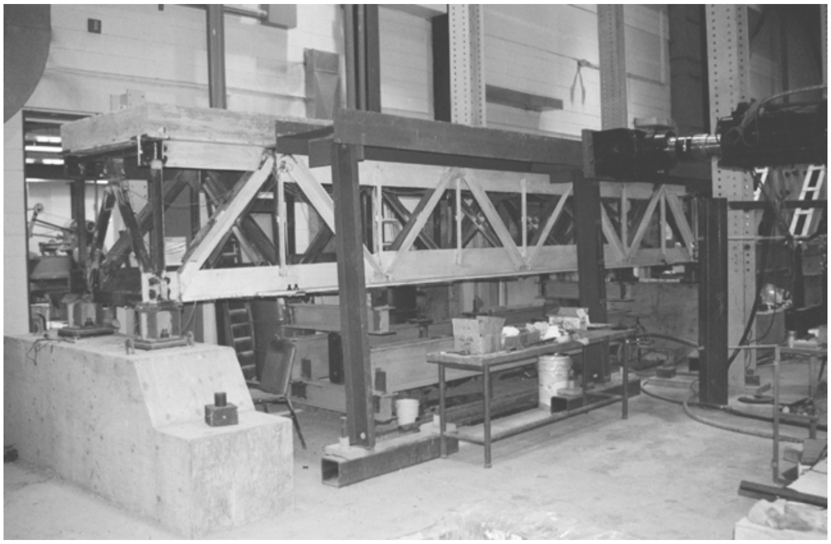

Figure 2. *An overall view of the 27-ft bridge model*

These cyclic tests were followed by pseudo-dynamic tests using El Centro earthquake ground motions scaled to peak ground acceleration of 0.5 g and 0.85 g. Overall response of the bridge was ductile with no damage observed in the cross-frames or lower lateral bracing members, considered the most vulnerable truss members. Similar ductile performance was observed for the same magnitude of El Centro Earthquake when the bridge was retrofitted with eccentrically braced frame. Figure 4 shows the force displacement curve obtained from pseudo dynamic test. The link beams exhibited strain ductilities as high as 12 and exhibited a robust hysteretic behavior (Figure 5).

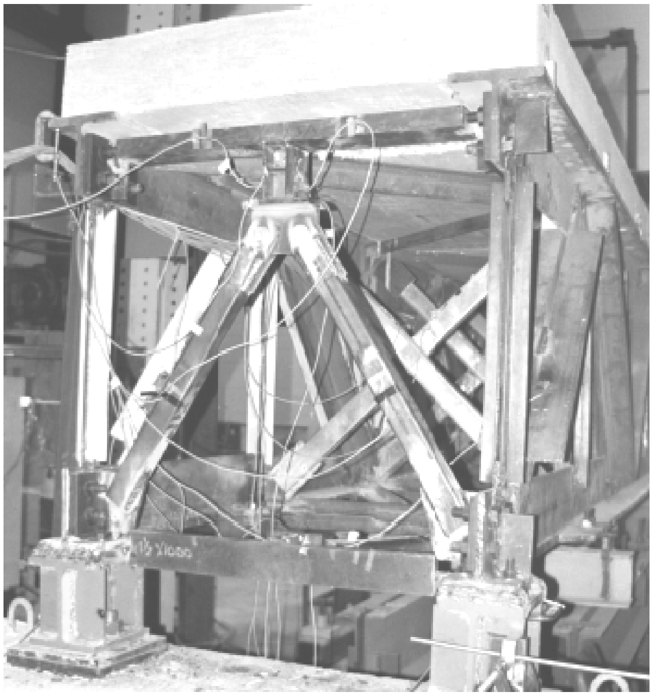

Figure 3. *Steel ductile retrofit at the end panel*

Another important observation is the effect of continuity of the concrete deck and its contribution to the stiffness of top lateral bracing system. Discontinuity of the concrete deck in the as-built condition due to expansion joints does now allow the in-plane stiffness of the concrete deck to contribute to the stiffness of the top lateral system and more uniform distribution of the forces transferred to the intermediate cross bracing members. Casting composite concrete deck as part of retrofit measure also contributed to the stiffness of the top lateral bracing system. This was confirmed by the measurements of the lateral displacements along the deck and comparisons to the lateral displacements of the top chords during the as-built testing where no concrete deck was cast on the top chords. No shear failure of studs or cracking in the concrete was observed.

After successful completion of the pseudo-dynamic tests, a final cyclic test was performed for each retrofit to measure ultimate capacity of the ductile links. Both specimens exhibited substantial overstrength. Finally, the failure caused by the fracture of the welded connections to the yielding devices in the end panels, which were measured at 800 kN and 740 kN for EBF and VSL retrofitted bridge, respectively, sustaining a global displacement ductility of 3 and 2. Figure 9 shows the shear deformations of the link beam in EBF and VSL retrofits.

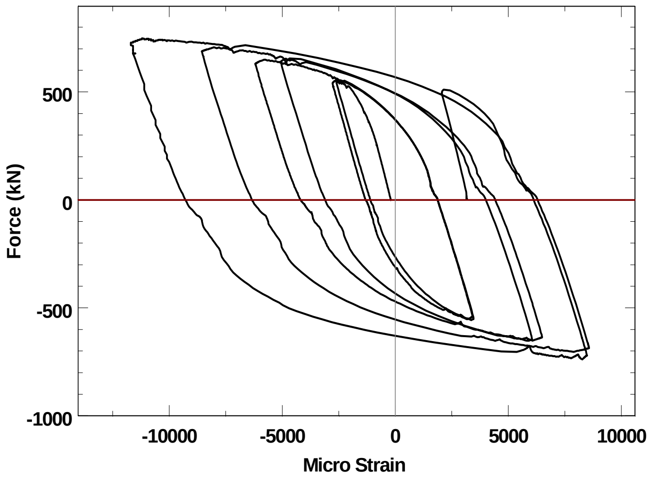

Figure 4. *Hysteretic response of ductile steel retrofit link*

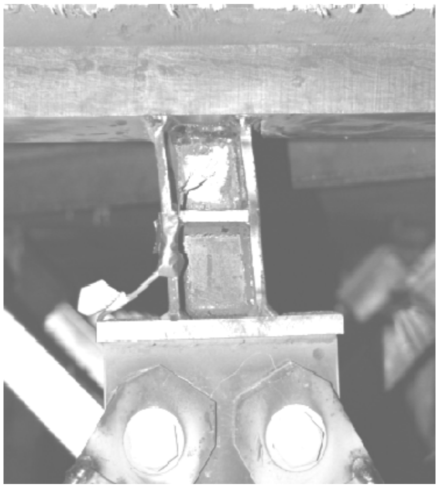

Figure 5. *Inelastic deformation of vertical shear link*

CONCLUSIONS

The results of pseudo-dynamic and cyclic tests performed on two different configurations of ductile energy dissipating devices (eccentrically braced frames, EBF and vertical shear link, VSL) used in a 27-ft long seismic retrofitted deck-truss bridge and for the El Centro earthquake scaled to 0.53 g, indicated that such devices can be designed and used as viable alternative seismic retrofit in deck-truss bridges.

The designed devices exhibited considerable cyclic ductility. By yielding and dissipating the induced seismic energy, these devices performed as structural fuses and protected other members of the superstructure. The devices exhibited substantial overstrength, however, which needs to be taken into account when determining the yield capacity of such protective systems to avoid overstressing other super-structural and sub-structural components.

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