IMPROVING STEEL BRIDGES AGAINST EARTHQUAKE THROUGH THE USE OF FLEXIBLE LATERAL DIAPHRAGMS

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Abstract

In earthquake zones, bridges are designed in such a way that the entire earthquake energy and its subsequent damages are directed into substructure parts (such as pillars, piers and bearings). This causes a critical issue particularly for old steel bridges with non-flexible substructures. In order to take advantage of steel structure of a bridge, a periodic strengthening method is suggested. In this method, fundamental damages to the substructure can be prevented by substituting flexible diaphragms for steel diaphragms in bearings and piers. This paper presents a brief summary of flexible diaphragms design method for seismic strengthening of steel bridges (with steel main beam and concrete slab), describes the related concepts and also analyzes the test results for diaphragm samples. Some tests in which the flexible lateral diaphragms with SPS, EBFs and TADAS (systems of dissipation of earthquake energy) had been used were performed on full-scale samples from the end part of a steel bridge with the span of 40 meters. According to the results of the tests, high resilience and high resistance against dissipation of Hysteresis energy were quite obvious. Fracture of resisting plates through bending status or link beam base loss through buckling and fracture of wings were the main causes of damage for flexible diaphragms in large lateral drifts. Although lateral bearings had not been used in these samples, they showed high formability capacity.

Keywords:

Introduction

Recent earthquakes such as those occurred in Northridge and Kobe clearly illustrated the seismic vulnerability of steel bridges with non-flexible substructures. Although the superstructure elements of these steel bridges experienced some damages such as buckling of parts and fracture of bracing joints of diaphragms, damages to the sub-structural parts such as bearings, pillars and foundations had some more destructive consequences and often

caused destruction of the span. Hence, when the seismic strengthening of current bridges matters, a good deal of attention goes to these sub-structural parts. Current methods for improving bridges include strengthening the existed non-flexible elements, increasing their formability capacity and replacing them with new proper parts or decreasing side forces by using Foundation Split method or other structural adjustments. In spite of proven effectiveness of these methods, none of them use the issue of Superstructure formability which includes the steel mean beams. Even the Foundation Split method, that decreases the level of earthquake forces, merely makes some changes in bearings. In addition, conducting aforementioned methods imposes extra coasts to the bridge strengthening procedure and bears some operational problems.

In order to take advantage of the formability of steel superstructure of bridge, the periodic seismic reinforcement method with flexible end diaphragms is proposed. Substituting flexible diaphragms which pass the yield strength before reaching the substructure strength for steel diaphragms in bearings and piers can prevent fundamental damages to the substructure. Recent literature shows the effectiveness and implementation of passive earthquake energy dissipation methods. Amongst these methods, Triangular-plate with Added Damping and Stiffness (TADAS), Eccentrically Braced Frames (EBF) and Sliding Panel Systems (SPS) are more common in building applications. However, the mentioned effective methods have not been used in construction process of stairs cause of which may be the lack of proper regulations for seismic designing and strengthening of stairs.

This paper presents a brief summary of flexible diaphragms design method for seismic strengthening of steel bridges (with steel main beam and concrete slab), describes the related concepts and also analyzes the test results for diaphragm samples.

Concept of Seismic improvement

The proposed method of improvement with flexible end diaphragms has been developed based on the capacity design. This method makes all the non-resilient deformations occur only in parts which have the ability to sustain the whole seismic energy. So, the imposed forces do not go beyond the threshold of elastic behavior formation threshold and the other parts of the structure will not need to have flexible elements. In other words, some specified flexible parts such as structural fuses provide capacity protection for the rest. By placing structural fuses within the end diaphragms of steel superstructure damages to non-flexible parts of substructure such as bearings, piers and foundation will be prevented. Hence, end diaphragms should be designed so that the formability behavior and constant Hysteresis

curves within the range of predicted loads remain smaller than the range of forces which cause unacceptable damages to the substructure.
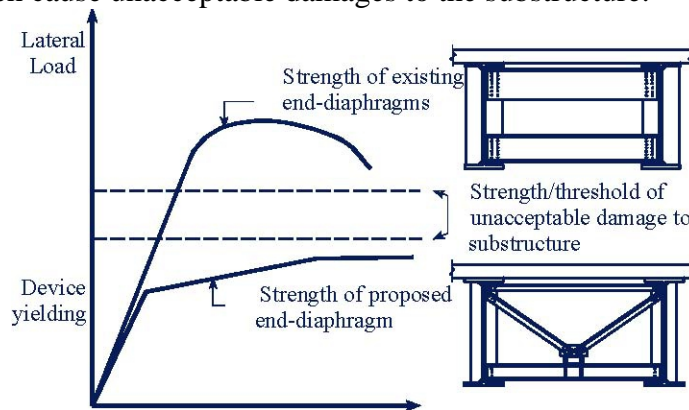

Fig.1 Non-resilient behavior of flexible end-diaphragms in comparison with current behaviors

Analytical Examination and Design Method

In order to provide more accurate calculations and form a simple design method, a simplified 2D model was used to study the 3D behavior of steel bridges. The proposed model consists of a flexible end diaphragm, limited lengths of 2 steel main beams with imposed supporters which have been modeled as flat bending parts, a certain length of the concrete slab and a small-scale spring-mass system in the dock balance to take the impacts of extended mass and stiffness into account. Figure 2 shows one of the samples.

Fig. 2: a sample which is being gradually prepared for test

Not only can 2 next models be directly involved in computer analysis, but also are easy to use in hand calculations. Additional data about the impact of main beam stiffness and its role in lateral loading and design

method details can be found in references 6 and 7. The step-by step design method for designing flexible end diaphragms is briefly described as follows:

1)   Determining fundamental parameters of the design (e.g. mass, seismic velocity, geometry)

2)   Calculating extended mass and stiffness

3)   Determining resilient shear strength and non-resilient shear strength of diaphragm by taking into account the design standards, the limited seismic capacity of the substructure and a part of the shear which is beard by some energy dissipater elements.

4)   Providing appropriate formability details for energy dissipater elements and designing all of structural parts and diaphragm joints in a way that they can bear loads 1.5 times bigger than the yield strength of those parts.

5)   Comparing the resulted period for flexible end diaphragm with the one considered in step 3 and repeating the previous steps until the values come as close as possible.

6)   Determining the value of true load decrease coefficient by using 2-lines or 3-lines behavior of diaphragm system and comparing the resulted value with the target value

7)   Repeating the previous 6 steps until the desired load decrease coefficient is gained (2 or 3 times, generally).

Test Method

To certify the analytical results and predicted structural behavior, some cyclic tests were performed on full-scale samples each of which had one flexible end diaphragm placed between 2 steel main beams (it shows a steel bridge with a 40 meters-wide span and 4 main beams). Each sample consists of two 50cm-long pieces of WWF1200x 333 profile placed in such a way that the center to center distance is 2 meters; 100mm-wide and 10mm-thick base transverse stiffeners in both sides of the base and a 200mm-thick armed concrete slab which is attached to the upper wings of main beams by 10mm-thick shear joints (Fig. 2). SPS, EBF and TADAS flexible diaphragms possess the V bracing with a lower beam and 2 laths as the diametric bracing frame. In designing and building the samples, yield strength and final strength have been set to be 350 Mpa and 450 Mpa respectively and the 28-days strength of concrete has been set to 30 Mpa.

Designing Test Samples

All of test samples were produced based on the proposed design method to face the maximum velocity of 0.6g which is the same for great earthquakes. These samples possessed only one flexible end diaphragm within every bearing. So, in order to run tests in the full-scale condition, only

2 man beams with a flexible diaphragm in between has been considered operational (Figs. 2 and 3). In designing samples, rigid links were used for lower wings, although, in action, joint links come to scene and improve the functionality of flexible diaphragms. Figure 3 shows the foundation framing and rebar placing prepared for concreting, as well as the rebar placing of concrete slab.

Fig.3: foundation framing and rebar placing and rebar placing of concrete slab

Equipping the Test

Necessary equipping was conducted to impose the vertical and horizontal loads to test samples. For vertical loads, a loading beam which was merely designed for this purpose was used. Also, a response frame was implemented for holding the lower part of horizontal jack to impose the lateral loading.

Fig.4 Equipping the test includes placement of loading frames and holders of test samples

Installing Measurement Devices

To measure the drift and strain in certain points, all samples were equipped with measurement devices. To increase the accuracy in determining displacements, a Temposonic with the stroke length of 50cm and the precision of 0.0077mm was used. In other points, a LVDT with the stroke length of 5 cm and the precision of 0.0034mm was used to measure the drift.

Loading method

3 MTS hydraulic jacks were used to impose the desired loads on the samples (2 jacks for vertical loads and 1 for lateral loads). Ergometers which had been installed on the jacks recorded the imposed loads. Constant gravity load of 350 KN was considered in such a way that it produced the same real impacts as P-Δ. Periodic drift history was chosen in such a way that 3 cycles are orderly imposed in lateral driftof ±0.25%, ±0.5, ±0.75%, ±1 %, ±1.5%, ±2%, ±3%, ±4% until the detachment occurs.

Test Results

In total, 8 tests were conducted on SPS, EBF and TADAS samples under different conditions. Due to the limit on the number of the words for this paper, only TADAS and EBF test results will be shown here. To find more data on the results of other tests, place check reference No.8. Before the fracture of bending plates which occurred at lateral drift of 4%, TADAS sample underwent 21 rounds of lateral loading. Final lateral load-Drift curve for this test is shown in fig. 5. The contraction (depreciation) seen in the curve is due to the slip of bearing and the error of initial free space at the top of triangle plates.
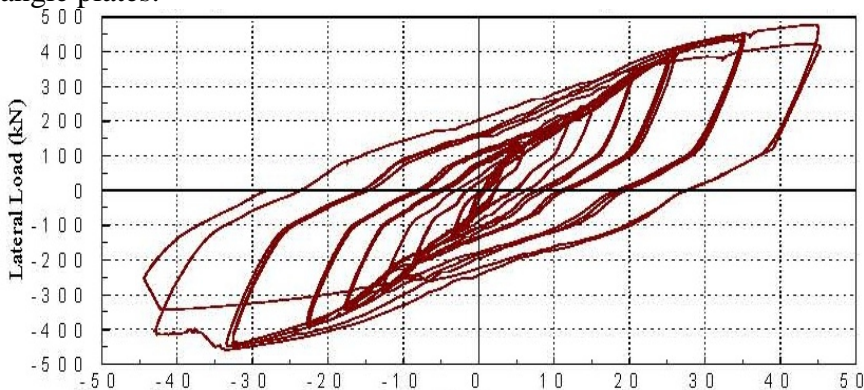

Fig.5 Hysteresis curve for test sample with TADAS flexible diaphragm

Results of measured strains showed that some triangular plates started to yield from the lateral drift of 1%. When lateral drift reached

20mm threshold (1.5%) (Equal to lateral force of 320KN), all of triangular plates yielded and some small cracks gradually occurred at the top of them.

As it can be seen in figure 6, triangular plates were clearly bended through the drift cycles of 25mm (2%) and a significant non-resilient deformation was observed. The test finished while 3 triangular plates were broken due to bending and base transverse stiffeners in main beam elements were partly buckled.
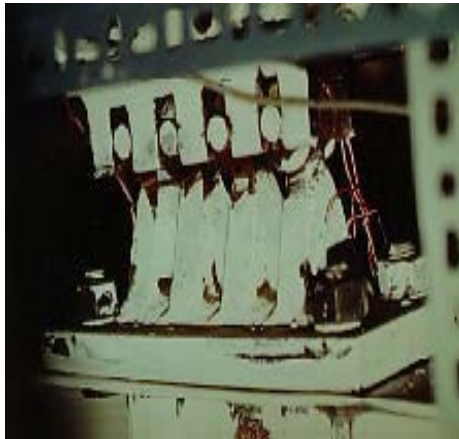

Fig. 6 Triangular plates experience hard bending status in lateral drift of 2%

To remove the deformations caused by slips in joints, EBF diaphragm sample underwent the welding process. Welding, as an improvement method, can be considered as a substitute for screw joints. Figure 7 shows the Hysteresis curve for this test in which 22 loading cycles were imposed to the sample. At the maximum drift of 30mm (2.5%), link beam disappears due to sudden lateral drifting and furling. Figure 8 shows the bending deformations of link beam. Buckling and brittle fracture at the end wing of link beam follows that instability. Providing lateral support for link beam may postpones this fracture.
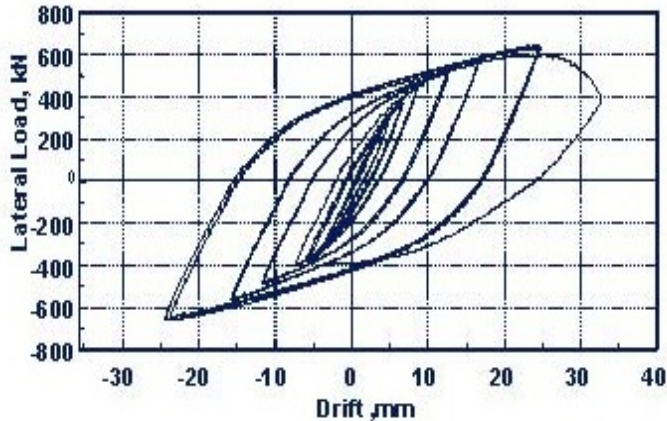

Fig. 7 Hysteresis curve for a test sample with EBF flexible diaphragm and welded joints

Fig. 8 Large shear deformations in link beam which shape it like a parallelogram

Conclusion and Suggestions

This paper presents a brand new method to have steel bridges (with steel main beam and concrete slab) and even modern bridges seismically improved. By taking advantage of the steel structure of bridge, flexible diaphragms which possess s set of systems for dissipating earthquake energy can be replaced with steel diaphragms in bearings and piers to prevent fundamental damages to the substructure.

A simplified design method for hand calculations was provided. Results of the tests conducted on full-scale samples from the end part of a steel bridge with the span of 40 meters showed high initial resilience and large resistance and capacity for dissipating Hysteresis energy. Bending period capacity of 0.2 radian for triangular plates and the shear deformation maximum angle of 0.11 radian which is the same as flexibility of 14 for link beam before its final fracture were observed. Fracture of resisting plates through bending status or link beam base loss through buckling and fracture of wings were the main causes of damage for flexible diaphragms in large lateral drifts. Although lateral bearings had not been used in these samples, they showed high formability capacity.

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