SEISMIC RESPONSE OF SHORT AND MEDIUM SPAN BRIDGES EQUIPPED WITH ENERGY DISSIPATING SHEAR KEYS

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ABSTRACT:
This paper presents the results of an analytical study conducted to evaluate the performance of short and medium span bridges using an innovative energy dissipation system aimed at improving seismic response of bridges. The energy dissipation system consists of ordinary rubber bearings which transfer the gravity load to the substructure and energy dissipation devices which replace shear keys on bent caps and abutments. In this system the bearings do not provide much resistance to lateral load. The device which is fabricated by metallic components would resist the lateral load and dissipate the seismic energy during an earthquake. Nonlinear time history response of a bridge structure with and without the energy dissipation system is studied. The most common type of structure for short and medium span bridges is considered. The bridge structure is subjected to various earthquake records including El-Centro, Tabas, Kobe, and Bam. The results of this study indicate that seismic demand of substructure is greatly reduced when the energy dissipation devices replace the shear keys on the bent cap and the abutments.

KEYWORDS:
Bridge, Earthquake, Structure, Shear Key, Energy Dissipation

1. INTRODUCTION

Bridges are an important link in surface transportation network and failure of bridges during an earthquake may cause very costly disruption to traffic and seriously hamper the relief effort. Modern bridge design codes [1, 2, 3] are based on the philosophy of accepting minor or even major damage but no structural collapse during a strong earthquake. They allow inelastic response and structural damage only at locations within the bridge that are both detectable and repairable. The preferred locations for inelastic behavior on most bridges are bent columns, pier walls, bearing and shear keys. Significant inelastic response of superstructure, bent cap, or foundation is not desirable because damages at these locations are difficult to inspect and repair and may prevent the bridge from being repair to a serviceable condition. However, there are many existing bridges all over the world which do not meet these basic requirements and are vulnerable to collapse or undesirable damage during a strong earthquake.

When bridges are subjected to strong earthquake, substantial amounts of seismic energy would be imparted into the bridge structures and may cause them to deform excessively or even collapse. In order for the structures to survive, they must have the capability to dissipate this input energy through either their inherent damping mechanism or inelastic deformation. Due to their structural simplicity, most bridges have low inherent damping and therefore, severe damage or collapse can occur by relying only on inherent damping and inelastic deformation. For the last three decades, bridge engineers have searched for innovative ways to dissipate the seismic energy and hence control its structural response to earthquake motions. These efforts have resulted in the development of various seismic isolation devices [4-10] and energy dissipation equipments [11-13].

This paper presents the results of an experimental and analytical study an innovative energy dissipation system aimed at improving seismic response of simple span and continuous girder bridges. The energy dissipation system consists of conventional elastomeric bearings which transfer the gravity load to the substructure and energy dissipation devices which replace shear keys on bent caps and abutments. In this system the bearings do not provide much resistance to lateral load. The device which is fabricated by metallic components would resist most of the lateral load and dissipate the seismic energy during an earthquake. This system could also be used for seismic retrofitting of existing bridges by replacing the conventional shear keys with the energy dissipation device.

2. CONCRETE SHEAR KEY

Concrete shear keys are usually constructed on abutments and bent caps to provide lateral restrain for the superstructures which are supported on conventional elastomeric bearings. An experimental research [14] has also been carried out at the University of California-San Diego (UCSD) to study the seismic response of concrete shear keys. The experimental results indicate relatively low energy dissipation of interior concrete shear keys especially after the first loading cycle. Figure 1 shows the typical failure mode of the concrete shear key. The typical load-deflection curve shown in figure 2 indicates low energy dissipation and rapid degradation after the first load cycle.

Figure 1- Typical failure mode of concrete shear key [14]

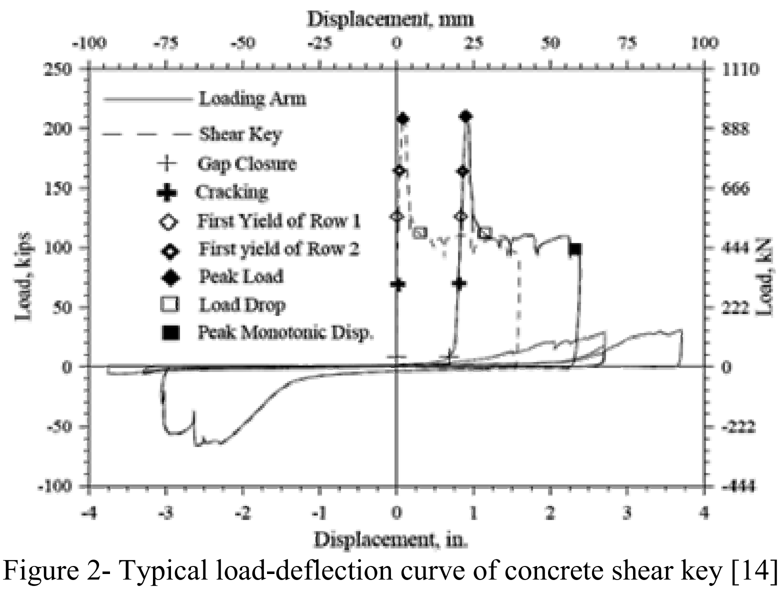

Figure 2- Typical load-deflection curve of concrete shear key [14]

3. ENERGY DISSIPATING SHEAR KEY

In the proposed alternative special shear keys with high ductility and energy dissipation capacity replace the ordinary concrete shear keys. An experimental program have been conducted to verify the performance of these shear keys under cyclic loading condition [15]. Figure 3 shows a typical load vs. displacement curve obtained from the experiments. As shown in this figure the proposed shear key have stable behavior without any degradation in strength under cyclic load. The tests show that the shear key is able to withstand a large number of cycle at large inelastic displacements before any failure. During an earthquake the special shear key serve as structural fuses to control damage in the substructure under transverse seismic loads.

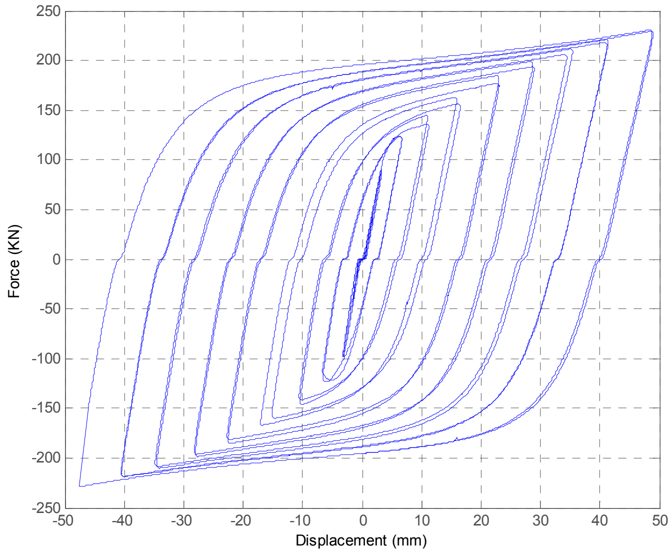

Figure 3- Typical load displacement curves of the special shear key

4. ANALYTICAL STUDY

A two span bridge with equal span lengths of 20 meters is considered for this study. Figure 4 shows the cross section of the superstructure. Each span consists of six simply supported precast concrete girders spanning between an interior bent at middle and an abutment at either end of the bridge. The girders are supported by laminated rubber bearings at each end. The surface dimension of each bearing is 30^{cm} x 30^{cm} and its height is 4.9 centimeter. Shear keys are placed on bent cap and on the abutments to restrain transverse displacement of the superstructure. The girders are free to move on the rubber bearings in longitudinal direction.

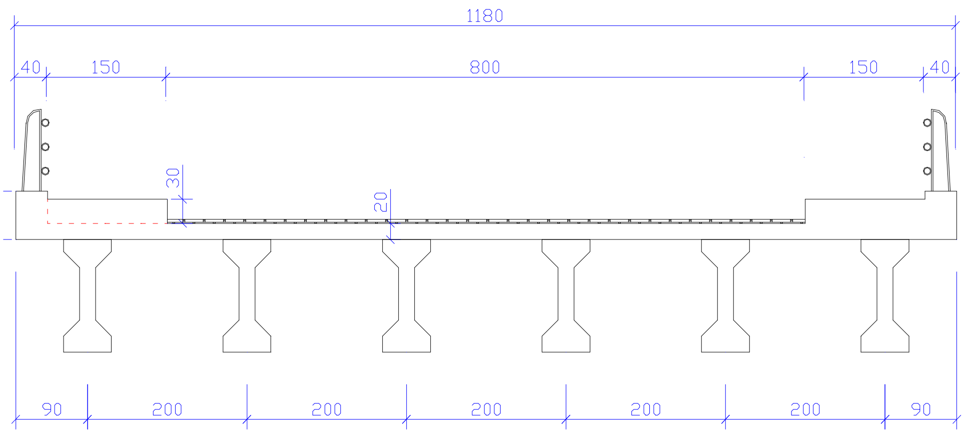

Figure 4 - Cross section of bridge superstructure

Figure 5 shows details of the interior bent. It consists of three reinforced concrete columns with a diameter of 120 centimeter. The columns which are supported on pile caps are seven meters tall. The bent cap cross sectional dimension is 120^{cm} by 80^{cm}.

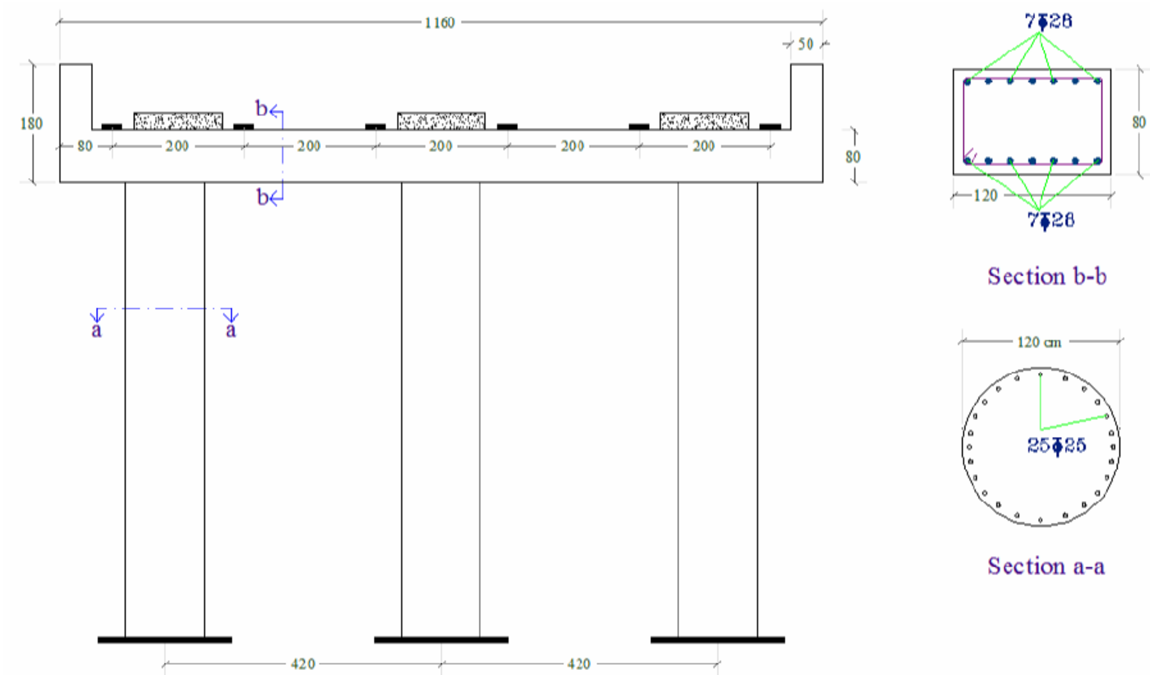

Figure 5 - Interior bent

4.1. Description of FEA Model

Figure 6 shows the FEA representation of the superstructure. The girders are modeled using shell elements for the web and frame elements for top and bottom flanges. The concrete slab which is modeled by shell elements is connected to the top flange by rigid link elements. This model places the mass of each component of superstructure at suitable locations. Mass of wearing surface, 270 kg/m^2, and mass of guard rail, 100 kg/m, are also added to the structural mass.

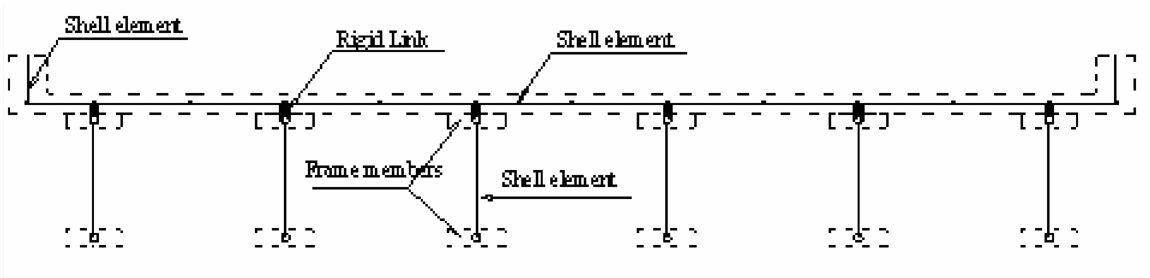

Figure 6 - FEA representation of the superstructure

Figure 7 shows the FEA representation of the interior bent. The columns and bent cap is modeled using frame elements. The columns are fixed at pile cap interface. The abutment at each end of the bridge is assumed to be rigid.

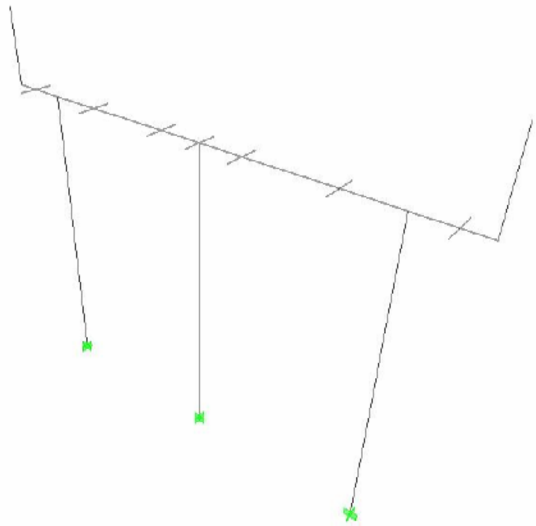

Figure 7 - FEA representation of the interior bent

The rubber bearings are modeled by spring elements. The stiffness properties of the spring in either direction are calculated from following equations.

Vertical stiffness: $$k_v = \frac{GA_b a^2}{Cnt^3} \tag{4.1.1}$$

Rotational stiffness: $$k_\theta = \frac{GA_b a^4}{C_1 nt^3} \tag{4.1.2}$$

Shear stiffness: $$k_u = \frac{GA_b}{nt} \tag{4.1.3}$$

Torsional Stiffness: $$k_\phi = \frac{GC_2 a^4}{t} \tag{4.1.4}$$

Where:

G = shear modulus = 1.6 Mpa.
A_b = bearing area
a = length of square bearing
n = no. of elastomer layer
t = layer thickness
C, $C1$, $C2$ = dimensional coefficients

Table 1 lists the stiffness properties of the rubber bearing as calculated from the above equations.

Table 1- Stiffness properties of the laminated rubber bearing

dimensions (mm)	k_v (kN/m)	k_θ (kN.m)	k_u (kN/m)	k_ϕ (kN.m)
300 x 300 x 49	1359000	243.4	3790.0	48.0

4.2- Results of Analytical Study

Seismic performance of the bridge with the two different types of shear keys on the bent cap and abutments is studied. In the first group of analyses the ordinary concrete shear keys are modeled by constraining the transverse displacement of underside of superstructure to the cap beam and the abutments. In the second group of analyses nonlinear springs are used instead of the above constraint to model the proposed shear keys. The analyses consisted of static push-over analysis to determine the capacity, and dynamic time history analysis to determine the demand under transverse seismic excitation. The earthquake records of El-Centro, Kobe, Bam, and Tabas with PGA of 0.7g are used for the time history analyses. Figure 8 shows the earthquake records.

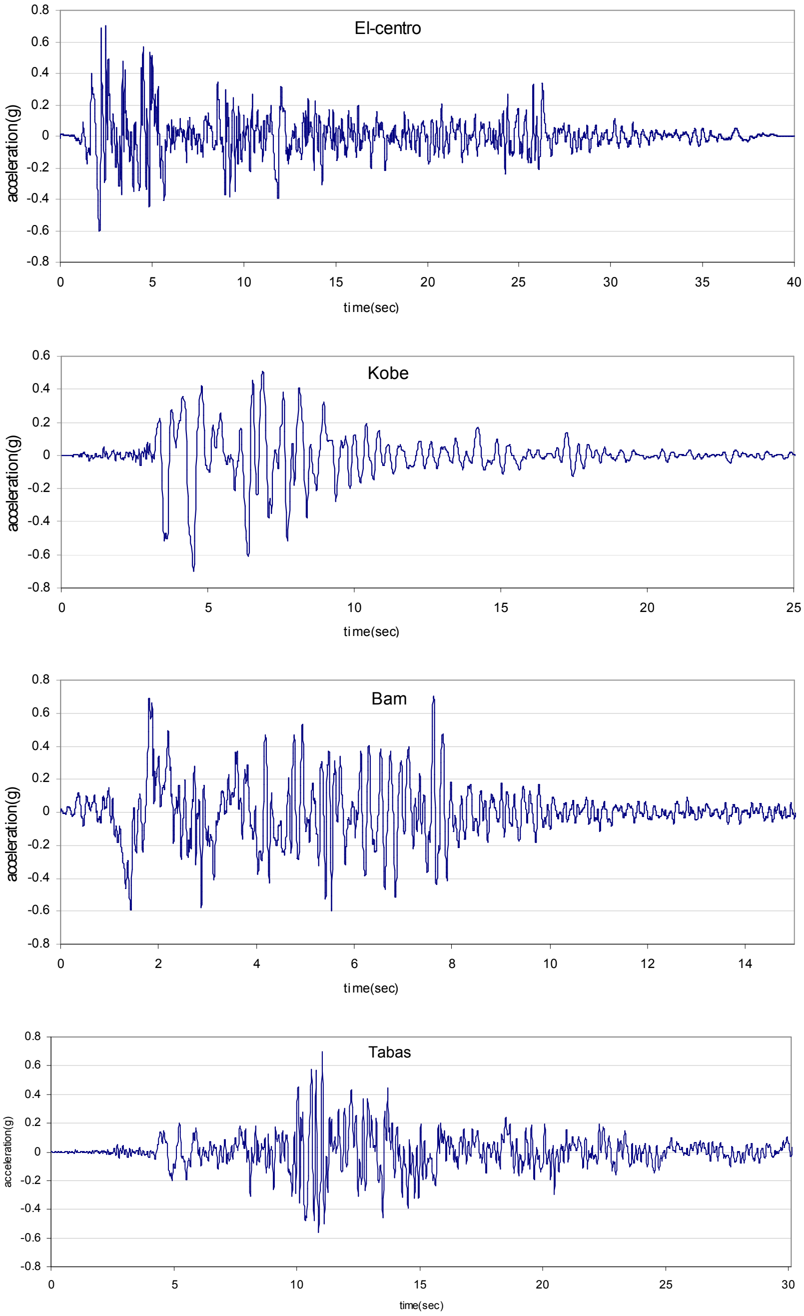

Figure 8- Earthquake records

Figure 9 shows the displacement capacity and displacement demand at the top of the interior bent. The sudden drop of the capacity at displacement 2.8^{cm}, 2.9^{cm}, and 3.9^{cm} is due to flexural-shear failure of the cap beam. This type of failure is not desirable because it is not easily repairable. For the case where concrete shear keys are used the peak displacement demand varies between 3.4cm to 6.2cm. At these displacements flexural-shear failure occurs in the bent cap. When steel shear keys replaces the concrete shear keys, the displacement demand reduces by at least 50 percent. As shown in figure 20 the maximum displacement demand reduces to less than 2 centimeters which is well below the displacement associated with bent cap failure. Figure 10 shows the time history displacements at the top of interior bent for the four cases.

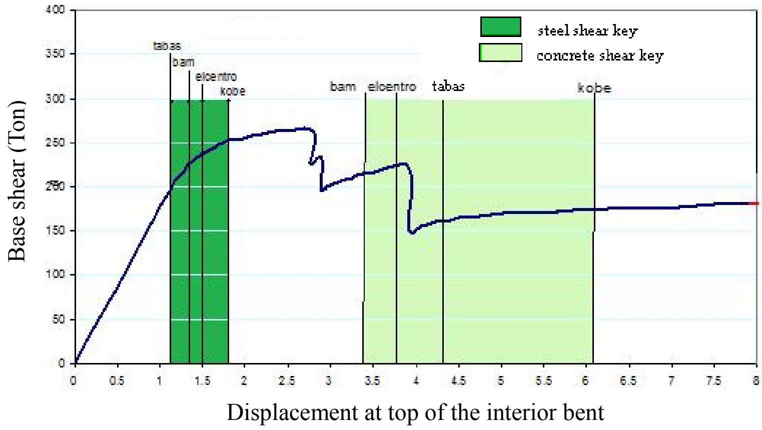

Figure 9- Displacement capacity and demand of the interior bent

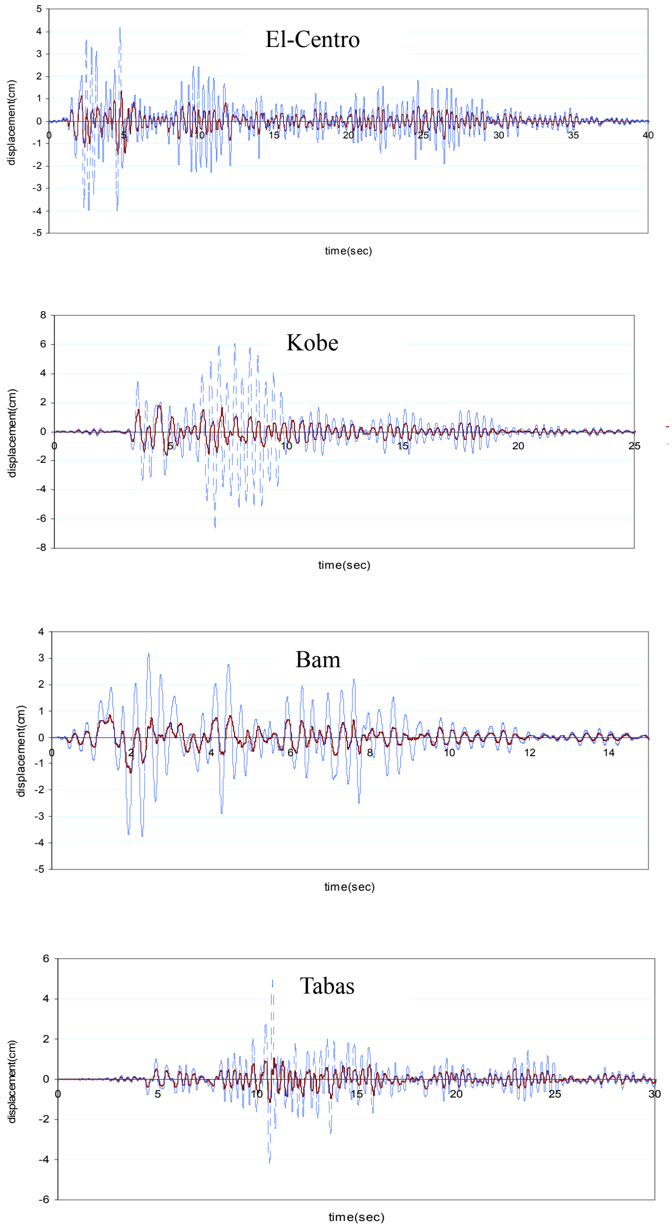

Figure 10- Displacement time history at top of interior bent

5. SUMMARY AND CONCLUSIONS

An energy dissipation system aimed at improving seismic performance of simply supported or continuous girder bridges is proposed. This system consists of ordinary rubber bearings which transfer the gravity load to the substructure and special shear keys which replace ordinary shear keys on bent caps and abutments. In this system the bearings do not provide much resistance to lateral load. The special shear key which is fabricated by metallic components would resist the lateral load and dissipate the seismic energy during an earthquake. An experimental study has verified that the proposed shear key has stable and suitable behavior under cyclic loads. An analytical study is also carried out to evaluate the seismic performance of a two span simply supported bridge with precast concrete girders. The analytical study is performed once with ordinary concrete shear key and once with the proposed shear keys. The analytical results indicate that the proposed shear key would substantially reduce the seismic demand of the substructure under transverse excitations.

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