Using friction dampers for improving earthquake response of self-variable stiffness RC framed buildings

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SUMMARY:
Effect of structural self-variable stiffness and friction dampers on earthquake response of RC framed buildings is investigated. Behaviour of a fully braced beamless RC frame is discussed. The role of pure concrete braces disengagement (with only constructive reinforcement) as a basis for a self-variable system is described. Up to a certain limit the frame itself controls its behaviour by adapting its dynamic characteristics during an earthquake. Such adaptation is achieved by concrete braces' disengagement under tension and their further non-linear action under compression during one oscillation cycle. The system has several adaptation levels, and it selects one of them for better response to the given earthquake. When the limit is reached, further self-adaptation of the frame becomes impossible. However, some earthquakes have more than one peak (Kocaeli 1999, Fucusima, 2011). Such earthquakes can lead to disengagement of the concrete braces after the first peak, intensifying structural damage and even causing collapse after the second one. The use of friction dampers can help to prevent the collapse of braces, enabling structures to withstand earthquakes with more than one peak.

Keywords: Sself-variable stiffness, earthquakes with more than one peak, friction dampers, concrete braces

1. INTRODUCTION

Seismic design generally considers structural ductility and inelastic deformation capacity (Iskhakov, 2003), but neglect the changes that occur in the building's static scheme during earthquakes with more than one peak having similar order of ground acceleration. In braced RC frames, for example, disengagement of concrete braces under tension yields a significant decrease in structural stiffness.

It was previously shown (Iskhakov, 2000) that a fully braced RC frame can change stiffness and adapt its dynamic characteristics to enhance its seismic response. In other words, the frame regulates its behavior, by disengagement of concrete braces under tension and using concrete non-linearity in compression. The system has several seismic regulation levels and selects one of them yielding the most suitable earthquake response. That regulation significantly reduces the seismic forces and dynamic displacements, creating an optimal structural scheme (Iskhakov, 2000).

When the structure's seismic resistance characterized by self-variable stiffness is not enough for a given region, a control system (Kobori and Kamagata, 1992; Ribakov and Gluck, 1999a and b) can be used. For example, active or semi-active variable stiffness devices can be applied to improve structural dynamic behavior (Nasu et al., 2003). In structures with self-variable stiffness (Iskhakov, 2000) supplemental control system selects the optimal stiffness, yielding a non-resonant dynamic behavior that results in a minimal peak response.

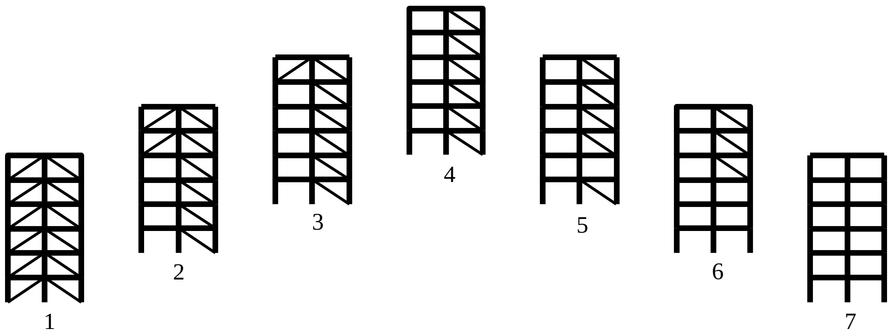
Various types of dampers may be used to realize structural control. Inaudi (1997) described a control strategy for semi-active friction devices. According to this study, the friction force between the sliding surfaces of a damper is proportional to its prior deformation peak. Xu et al. (2001) developed a piezoelectric semi-active friction damper and studied its efficacy in controlling the behavior of a tower under dynamic loads. Ribakov and Gluck (1999a) demonstrated that semi-active friction dampers incorporated at each floor level of an MDOF structure significantly reduced its seismic response.

In the frame of the present study a braced RC frame with self-variable stiffness is analyzed. Variable friction dampers can be used to increase the frame's ability to withstand high seismic loads when its seismic resistance capacity is inadequate for the given seismic zone. Implementation of the dampers is intended to avoid collapse of concrete braces under compression.

This study is aimed at developing conceptual design approaches for buildings that should withstand earthquakes with two or more peak ground accelerations. This issue looks very important in the view of recent earthquakes in Kocaeli (Turkey, 1999) and Fucushima (Japan, 2011). The design procedure described below can be applied to new structures as well as for retrofitting existing ones.

2. **SEISMIC RESPONSE OF A SELF-VARIABLE STIFFNESS RC BRACED FRAME**

Conceptually response of an RC braced frame to earthquakes with repeated peak ground accelerations (RPGA) can be explained using an example of a flat-slab building shown in Figure 1. The figure presents an initial scheme of the structure (scheme No. 1) and the schemes through which it passes under earthquakes with RPGA (scheme 2-7). The dimensions of the frame in the horizontal plane that were taken in the present study are 12×12 m, the distance between column axes is 6 m in both directions. Each story has a 3 m high and includes diagonal concrete braces in both bays. The cross sectional dimensions of the elements are as follows: columns 0.4 × 0.4 m, braces 0.2 × 0.4 m, floors 6.0 × 0.16 m.



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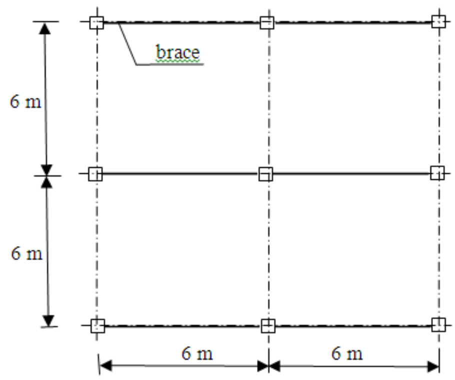


(b)

Figure 1. Changes in the basic frame scheme (a) and plan of the structure (b), following Iskhakov and Ribakov (2008)

The braces are reinforced in their middle part against the bending moment due to dead loads and have minimal reinforcement only in the zone near to the joints, which provides proper resistance under tensile forces in cracks. Additional data that was used for design are described in details in the previous study. The natural vibration period of the structure is 0.638 sec., the horizontal seismic forces, acting at each floor are 21.9 kN at the first story, 43.8 kN, 65.7 kN, 87.5 kN, 109.4 kN, 131.3 kN at the roof (Iskhakov and Ribakov, 2008).

The diagonal braces' axial load capacity is 960 kN under compression and 72 kN under tension. Tensile forces yield cracks and in the absence of reinforcement the braces would unilaterally disengage. Due to cyclic nature of seismic forces, the cracks close and the braces that were under tension are re-engaged under compression. The elasticity modulus of concrete decreases from cycle to cycle, but only until the compressive force reaches the load capacity in compression. A detailed explanation of this phenomenon from the energy dissipation viewpoint is given by Iskhakov (2003).

The brace adjusts itself to the earthquake, and energy dissipation increases from step to step. But if the load capacity in compression is exceeded, the brace disengages irreversibly and the natural vibration period of the structure increases respectively. In other words, braces have two disengagement levels: one under tension and one under compression.

3. SELF-VARIABLE STIFFNESS MECHANISM

Analysis of the frame (see Figure 1) was carried out for two cases of the stress-strain modulus (constant and variable) and for the following two load combinations: $F_g + 0.2\ F_q + F_D$ and F_D, where F_g and F_q are the dead and live loads, respectively, and F_D is the seismic load. The analysis demonstrated that, in the real time of the earthquake, the structure changes scheme by implementing brace disengagement in response to the peak forces (PF).

It was shown that vertical static loading plays an important role in self variable stiffness process (Iskhakov, 2003). When a brace is disengaged under tension and asymmetry is created, the structure's deflection sometimes acquire horizontal components running counter to the displacements due to seismic forces. Since, however, the latter depend on the structure's mass and the live load. Any increase in the seismic forces yields a corresponding increase in the counter-effect of the static loading.

With a reduction of the concrete elasticity modulus, unilateral or complete disengagement and static loading counter-effect substantially reduce the seismic forces (by over 50%), yielding a corresponding static scheme providing the most suitable structural seismic response. The structure "selects" the most appropriate static scheme for the current situation.

Figure 2 demonstrates the self-variable stiffness mechanism under an earthquake with RPGA. Representative examples of such ground motions are strong earthquakes that occurred in Kocaeli (Turkey, 1999) and Fukushima (Japan, 2011), shown in Figure 3.

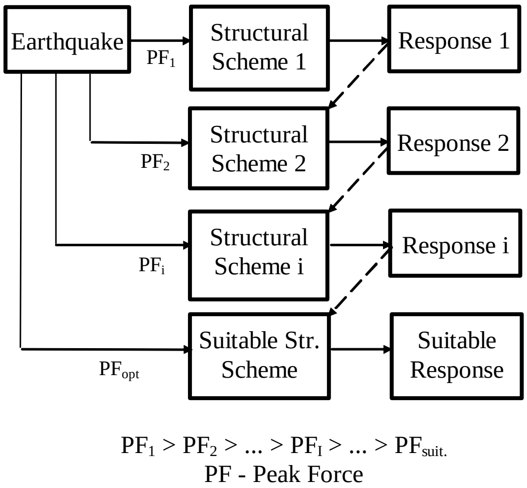


Figure 2. Schematic diagram of self-variable stiffness mechanism (following Iskhakov and Ribakov, 2008)

It was shown that a frame with self-variable stiffness adapts its response to the current earthquake by using the basic properties of concrete (Iskhakov and Ribakov, 2008). It selects a state with maximum energy dissipation, while reducing the seismic forces by almost one half. The system has several self-seismic control modes in terms of material, structure and loading and it applies the most suitable one, adapting itself to an earthquake with RPGA.

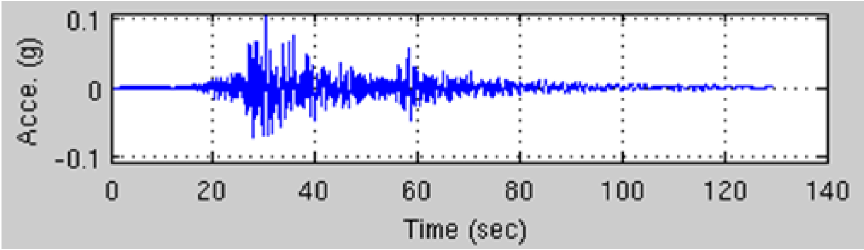
After the structure has passed the first acceleration peak its ductility increases. In a particularly strong earthquake, all the braces of the RC structure may be destroyed under compression. As a result, the structure becomes un-braced and under an RPGA significant damage will occur in structural elements or the building will collapse because the structural elements have relatively low potential for further plastic energy dissipation. Therefore using supplemental control adds artificial ductility (energy dissipation ability) that allows the structure to withstand further RAP.

4. PROPOSED CONCEPTUAL DESIGN PROCEDURE FOR RPGA EARTHQUAKES

The problem of RPGA earthquakes is important because if such type of ground motions occurred in one region, it is logically that such earthquakes can occur again. In order to obtain proper structural response to earthquakes with RPGA the following issues should be taken into account. The structure should be able to withstand at least two strong earthquakes without progressive collapse. All types of local damages, cracks, collapse of non-structural elements, plastic hinges and big deflections are allowed. Nevertheless, it should be clear already at the design stage that it will not be possible to retrofit such buildings after an RPGA earthquake. If the building can be retrofitted, than the allowed ultimate deformations should be lower than the yielding ones.

The next problem is how to provide the absorption of input energy from two earthquakes with strong PGA. For both of the above described cases an ideal solution is using appropriate supplemental energy dissipation systems (SEDS), allowing "dosing" of nonlinear deformations in the structure. If however for any reason it is impossible to use SEDS, the only solution is to use "dosed" ductility level of the structure, i.e. to apply at the design stage medium ductility level instead of high, or low instead of medium.

The above mentioned procedure can be also used for estimating seismic resistance and ductility of existing buildings. With this aim a structure should be analysed under a number of repeated earthquakes (an RPGA earthquake) with PGA, corresponding to the seismic area, for which the building is designed. In such a way a number of earthquakes the building is able to withstand for a given ductility level is found and proper ductility level for strengthening can be selected. It should be mentioned that the number of PGAs the building is able to withstand before collapse becomes an important design parameter.



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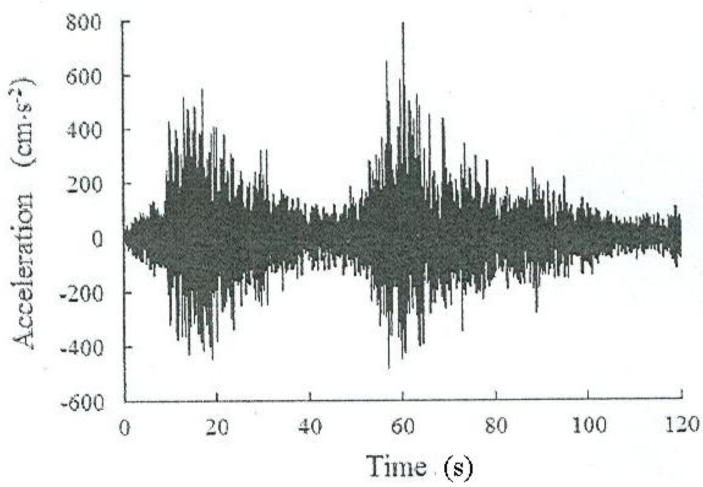

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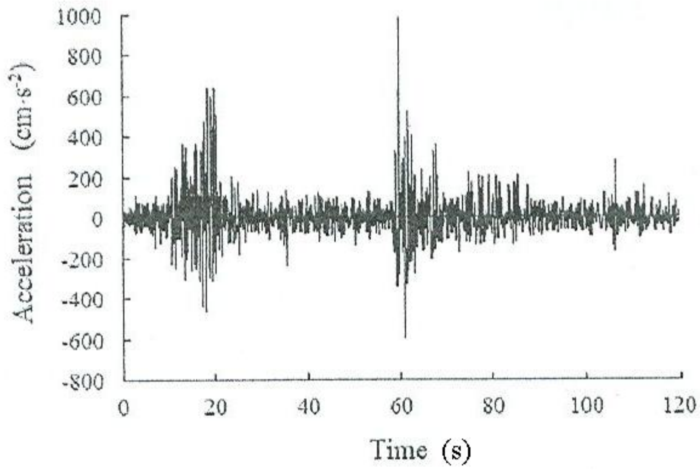

(c)

Figure 3. Ground motions with RPGA: (a) Kocaeli, Turkey, 1999; (b) Fukushima, Japan, 2011 – MIG003 station record; (c) Fukushima, Japan, 2011 – MIG013 station record

5. VARIABLE FRICTION DAMPERS

Passive variable friction dampers (VFD) are a rather cheap alternative to active and semi-active devices, having an advantage that, from one side, no energy is required for their activation, and from the other one, they add energy dissipation ability that increases as the displacements become higher

(Ribakov et al., 2006). A general scheme of VFD is shown in Figure 4. The device consists of a tube (1), a double-wedge (2), two elastic strip elements (3) and a bolted connection clip (4). The wedge is located partially inside the tube and can move ahead and back along its axis. The strips have a cantilever static scheme and are fixed on the tube by the connection clip, forming an elastic strip system. The stiffness of this system may be regulated by changing the location of the connection clip along the tube. The free ends of the cantilever strips have a contact with an inclined surface of the wedge.

The damping force, developed by VFD, depends on the friction between the wedge and the elastic strip elements and on the wedge geometry. The friction itself depends on the elastic strip elements flexibility. Hence, the VFD calculation scheme should include the following design parameters: the double-wedge geometry, the elastic strip elements length, cross section and material properties and the friction coefficient between the strips and the wedge.

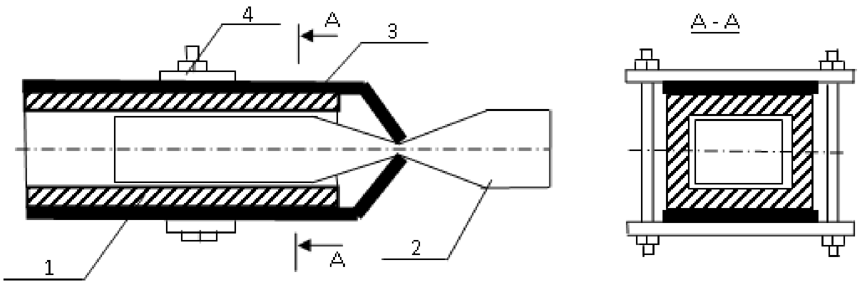

Figure 4. A scheme of VFD

A theoretical model for predicting the damping force was developed and verified experimentally for different wedge inclination angles and various elastic strips' flexibility values (Ribakov et al., 2006). It was demonstrated that increasing the wedge inclination angle from 15 to 30 degrees and decreasing the elastic strips flexibility by 1.5 – 2 times yield an enlargement of the hysteretic loops area up to three times. Therefore, selecting VFD with appropriate wedge inclination angle and elastic strips' flexibility allows achieving the required energy dissipation potential that corresponds to the design provisions from the ductility level viewpoint.

6. NUMERICAL EXAMPLE

Effectiveness of the variable friction dampers, described above, was demonstrated for the structure shown in Figure 1. Behavior of a self-variable stiffness RC frame with and without dampers was modeled for the Loma Prieta and Northridge earthquake records, scaled to PGA = 0.3 g. Figure 5 shows peak base shear forces obtained for the frame with and without the variable friction dampers under each of the selected earthquakes. In both cases the base shear forces were lower in the frame with VFD, the reduction achieved ranges between 5 and 10%.

Figure 6 presents peak displacements in the frame under the same earthquakes. As controlled frames are less stiff than uncontrolled ones and braces work only under compression, it is logical that controlled frames should exhibit greater displacements. Higher increase in frame displacements was obtained for the Loma Prieta and Northridge earthquakes, 20-60%.

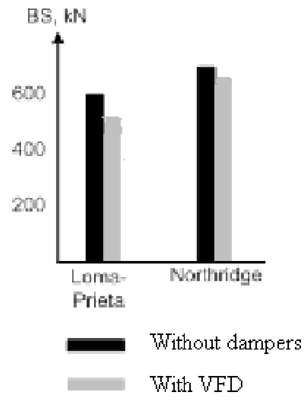

Figure 5. Peak base shear forces

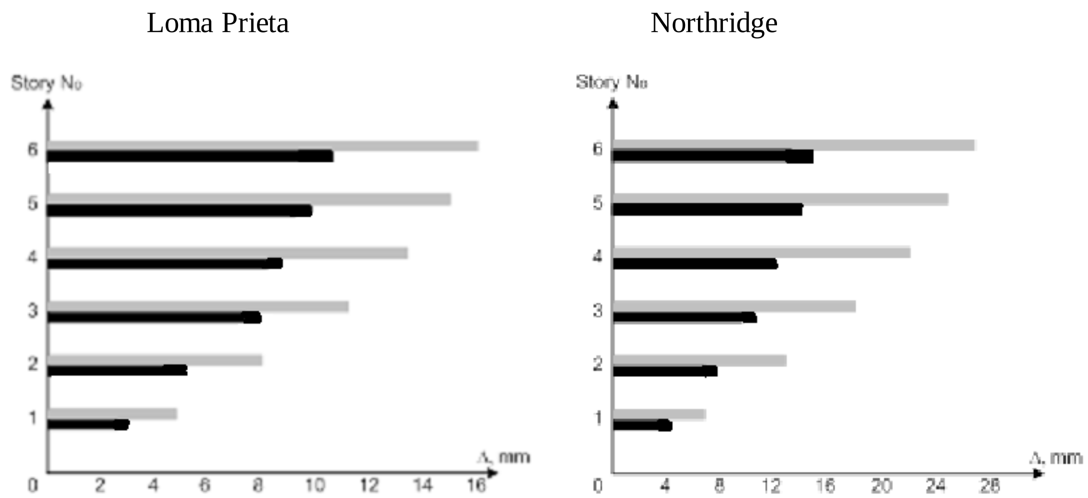

Figure 6. Peak floor displacements

When the seismic response of the uncontrolled structure is analyzed, the frame passes from scheme 1 to scheme 7 (see Figure 1) during the earthquake, and the base shear decreases only up to scheme 4. After that stage the base shear forces increase in magnitude due to additional bending moments, related to non-linear effects. However, the use of variable friction dampers provides an additional decrease in base shear, though displacements continue to increase. This result demonstrates that variable friction damping systems are effective in improving the behavior of deformed structures like active or semi-active devices.

7. CONCLUSIONS

The study was aimed at developing conceptual design approaches for buildings that should withstand earthquakes with two or more peak ground accelerations. This issue looks very important in the view of recent earthquakes in Kocaeli in Turkey, 1999 and Fucushima in Japan, 2011.

Influence of structural self-variable stiffness and friction dampers on response of RC framed buildings to earthquakes with repeated peak ground acceleration was studied. Step-by-step behavior of a fully beamless RC frame with pure concrete braces (including only constructive reinforcement) under such seismic loadings is shown.

It was demonstrated that up to a certain limit the frame itself controls its behavior by adapting its dynamic characteristics during an earthquake. This effect is obtained due to the braces' disengagement under tension and their further non-linear behavior under compression during oscillation cycles that are close to the time instants, when the PGAs appear.

An important issue is that a braced RC frame has several adaptation levels, and it selects one of them for better response to the given PGA. To provide proper input energy absorption from two or more earthquakes with strong PGA, appropriate supplemental energy dissipation systems (SEDS), allowing "dosing" of nonlinear deformations in the structure, can be used. If, however, for any reason it is impossible to use SEDS, the only solution is to use "dosed" ductility level of the structure. The proposed approach can be applied for estimating seismic resistance and ductility of existing buildings or design of new structures.

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