Numerical Investigation of Floor Isolation for Passive Earthquake Energy Dissipation

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ABSTRACT

Safeguarding structures against seismic loading is the principal outcome of sound earthquake design. Many techniques have been developed to achieve this, especially in relation to passive energy dissipation. This research proposes that isolating the floor slab of a building from the supporting beams will dissipate seismic energy and reduce the lateral forces imposed on structures. The variables controlling the behaviour of the isolation mechanism and the isolated floor slab were investigated for a two storey, single bay, concrete frame with fixed supports. Key structural response indices including inter-storey drift, storey shear, base overturning moment and others were evaluated for frames with and without a floor isolation mechanism under a representative earthquake design spectrum. Initial results illustrated that the lateral displacement of frames containing isolated floor slabs was substantially reduced compared to frames with traditional fixed floors. Smaller base shear forces and overturning moments were also experienced by models with the floor isolation system. Finally, structures with the isolation mechanism exhibited the capacity to do more work and thus dissipate larger quantities of energy than structures without the mechanism.

Keywords: passive, energy, dissipation, isolation, seismic, performance, response

1. INTRODUCTION

Seismic protection of structures has been attempted in various forms including the strength-ductility approach, the strong column-weak beam (SCWB) technique and structural control. Strength-ductility theory involves strengthening the primary structural elements whilst ensuring that members have sufficient ductility to accommodate large displacements. However 'design for strength alone does not ensure that the building will respond dynamically in such a way that the comfort and safety of occupants is maintained' (Housner et al. 1997, p. 897). Furthermore, structures designed using this technique frequently experience irreparable structural damage and considerable financial costs during earthquakes (Calio, Marletta & Vinciprova 2003, p. 2589).

The SCWB philosophy is an alternative approach where columns are designed with a larger moment capacity than the beams such that the beams yield prior to the columns. Upon yielding, plastic hinges develop at the ends of the beams permitting inelastic rotations. This significantly reduces the possibility of a soft storey; a situation where the base columns fail causing the collapse of the remaining stories (Williams 2007, p. 227). However, experience shows that a SCWB structure is difficult to achieve, primarily because a monolithically cast floor slab 'significantly increases the effective flexural strength of the [supporting] beam' (Derecho 1989, p. 287).

A third option is structural control: the process by which seismic energy is absorbed, transferred or dissipated through a structure (Calio, Marletta & Vinciprova 2003, p. 2589). Structural control devices control structural vibrations by 'modifying rigidities, masses, damping, or mode shape and by providing passive or active counter forces' (Housner et al. 1997, p. 897). This limits the imposed forces and resulting deformations on individual elements.

Structural control mechanisms are classified into four broad categories; passive, active, hybrid and semi-active systems. Passive isolation - systems which do not require any active intervention or supplementary energy sources (Hamburger & Scawthorn 2006, p. 4) - is the focus of this research. Metallic yield dampers (Chen & Eads 2005, p. 3; Housner et al. 1997, p. 899), friction dampers (Nims et al. 1993 in Housner et al. 1997, p. 902; Tsai et al. 2008, p. 2321), viscoelastic dampers (Chopra 2007, p. 283) and tuned mass dampers (Almazán et al. 2007, p. 1548) are commonly used passive dissipation devices proven to reduce seismic loading effects. Segmenting buildings is also considered a passive energy dissipation technique, where structures are divided into several segments interconnected via passive isolation systems (Pan & Cui 1998; Pan, Ling & Cui 1995). Compared to conventionally designed buildings, significant improvements in storey displacement have been achieved.

From the available literature, it does not appear that any prior research has been conducted on isolating the floor slab from the beams. Since a large proportion of the structural mass is contained in the floor slab, isolating this mass from horizontal motions was expected to significantly reduce structural damage and deformation due to seismic loading. Furthermore, the isolation system should dissipate seismic energy, decreasing the demands imposed on structural members. If successful, this technique could significantly improve the seismic safety and performance of various structures.

2. RESEARCH PROPOSALS

The primary aim of this research was to explore the seismic performance of structures containing floor slabs isolated from the beams via rubber bearings. This technique was postulated to have at least three beneficial effects on overall structural response. First, as the floor slab is free to vibrate independently of the primary frame the building will experience smaller lateral forces as a large proportion of the structure's mass is isolated in the floor slab. Second, the isolation system will absorb a significant proportion of the seismic input energy, reducing the quantity of excitation energy within the system. Finally, effectively implementing the SCWB design philosophy is expected to become significantly easier as the floor slab's contribution to the moment capacity of the structural beams will be substantially reduced or eliminated. Importantly, this research was intended as a preliminary study and as such practicalities including construction and installation details have not been considered. Provided the above hypotheses are proved correct, further work could be carried out into these aspects.

2.1. STRUCTURAL MODELS

The isolated floor system was assessed by numerical analyses of a reference structure without floor isolation (RC) and an isolated floor structure containing the mechanism (IC). The reference model was identical to the isolated case except the floor slab was rigidly connected to the supporting beams rather than via rubber bearing elements (Figure 1). Both the reference and the isolated floor structure consisted of a single seven metre wide bay, two storey concrete frame with fixed base supports.

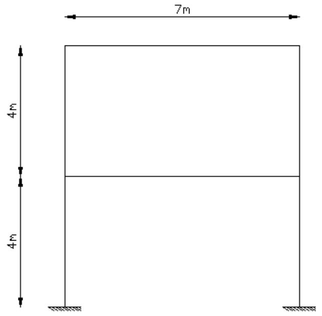

Figure 1 – Reference structure with fixed floor slab (RC)

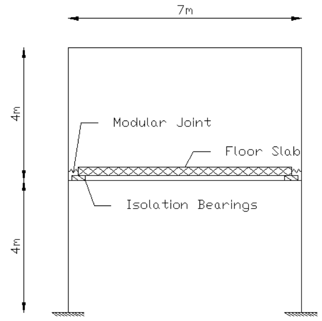

Figure 2 – Isolated floor case (IC)

The isolated floor model contained additional elements to isolate the floor slab from the supporting beams. These included rubber isolation bearings and modular joints between the floor slab edges and adjacent columns. The joints were required to span the clearance distance (Figure 2) left between the slab and column to accommodate floor slab vibrations. Table 1 and Table 2 provide details on the structural properties of the models analysed.

	Beams	Columns	Floor
Young’s Modulus (kPa)	30100	30100	30100
Stiffness Damping Factor, β	0.05	0.05	0.05
P-delta effects	No	Yes	No
Dimensions (mm)	450 x 300	450 x 450	7000 x 150
Cross-sectional Area (m^2)	0.135	0.2025	1.05
Moment of Inertia* (m^4)	0.00163	0.00145	0.00034
k_{ii}	4	4	4
k_{jj}	4	4	4
k_{ij}	2	2	2
Moment Overshoot Tolerance	0	0	0
Yield Surface Shape Code	1	3	1
Positive Yield Moment (kNm)	255.91	383.87	376.96
Negative Yield Moment (kNm)	255.91	383.87	376.96
Compression Yield Force (kN)	N/A	7423	N/A
Tension Yield Force (kN)	N/A	2025	N/A
M/M_y^+ (Point A)	1.1	1.1	1.1
P/P_{yc} (Point A)	0.3	0.3	0.3
M/M_y^+ (Point B)	1.1	1.1	1.1
P/P_{yc} (Point A)	0.3	0.3	0.3

Table 1 –Modelling structural properties for beam, column and slab elements

Isolation Bearings		Modular Joints	
Stiffness Damping Factor, β	0.05	Stiffness Damping Factor, β	0.01
k_1 (kN/m)	Varies	Displacement Limit, u_1 (m)	0.05
k_2/k_1	0.5	Displacement Limit, u_2 (m)	0.1
F_y^+ (kN)	2.98×10^{28}	k_1 (kN/m)	9070
F_y^- (kN)	2.75×10^{29}	k_2 (kN/m)	2700
Direction Code	1	k_3 (kN/m)	90.7
Elasticity Code	1	$k_4 = k_1$ (kN/m)	9070
		Initial Gap Size (m)	Varies

Table 2 – Modelling properties for isolation bearings and modular joints

2.2. GROUND MOTION RECORDS

Structural modelling was conducted using three ground motion records produced using the Newmark-Hall design spectrum normalised to 0.5 g with a duration of 20.475 seconds. The three records were identical in frequency and intensity contents, differing only in phase angle. Figure 3 gives the frequency and period spectrum of the three motions.

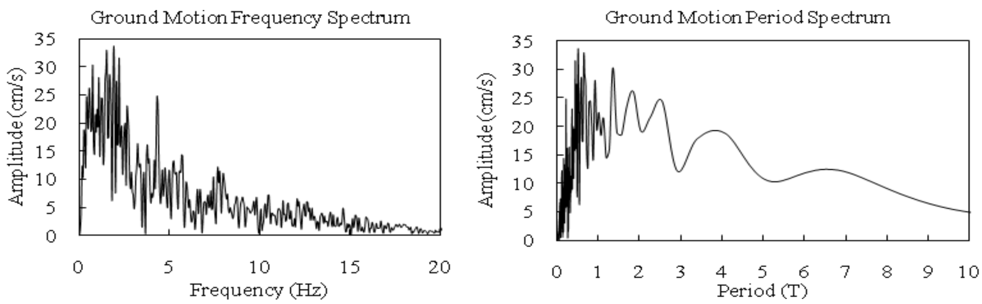

Figure 3 – Ground motion frequency and period spectrum

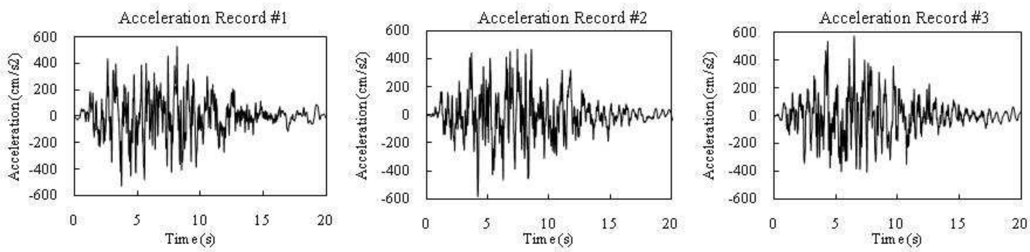

Figure 4 – Ground motion acceleration records

2.3. SEISMIC PERFORMANCE INDICATORS

Numerous indicators have been developed to assess seismic performance of structures, each with strengths and weaknesses in particular applications (Ghobarah, Abou-Elfath & Biddah 1999). The measures used within this research were selected based on their extensive use in a variety of situations as well as on proven accuracy and reliability. They include:

- Inter-storey drift ratio: relative displacement between consecutive stories normalised by the storey height
- Displacement time history: measure of maximum displacement of the first floor and roof

- Base shear force: shear force generated at the structure's supports
- Overturning moment: about the base as a result of structural deformations
- Modal analysis: modal frequency and primary mode shapes
- Impact forces: force applied to adjacent column due to slab-column pounding
- Kinetic energy: of each element within the structural system
- Static, viscous and external work: cumulative work done by the frame

These choices are consistent with the fact that damage in reinforced concrete is 'related to irrecoverable [inelastic] deformations, [thus] quantities which are commonly used are end rotations, inter-storey drift and storey shears' (Kappos 1997, p. 79).

3. RESULTS

3.1. ISOLATOR STIFFNESS & CLEARANCE DISTANCE

To investigate the complex interaction of the clearance distance, the lateral stiffness of the isolation bearings and the overall structural response, the clearance was held constant and the inter-storey drift ratios for the first floor and roof were computed. Figure 5 and Figure 6 show the inter-storey drift of the IC as a percentage of the RC for various clearances, defined as 'x' on the plots. Models containing the floor isolation system began to display superior performance compared to the RC when the clearance was between 0.2 – 0.3 metres. The three frames with clearance sizes within this range reached a minimum inter-storey drift of 77% of the RC for the first floor and 68% for the roof, albeit for different bearing stiffness. The model with a clearance of 0.15 metres reached a minimum inter-storey drift value of 80% for the first floor and 70% for the roof whereas the model with the smallest clearance of 0.1 metres did not reach any clear minimum, but decreased gradually and converged to 100% of the RC.

The inter-storey drift for all structures converged towards 100% of the RC as the bearing stiffness became very large; that is the inter-storey drift of the IC's and the RC converged. For all but the smallest clearance size model, as the bearing stiffness increased above the value at which the optimal point was reached, the inter-storey drift began to increase, reflecting the increasing rigidity of the bearings. Furthermore the significant increase in response when the stiffness or clearance size was low suggests substantial interaction between the floor slab and adjacent column through the modular joint. Low stiffness bearings or small clearance distances increased the frequency with which the slab pounds against the column. These pounding forces dramatically reduced the effectiveness of the isolation mechanism.

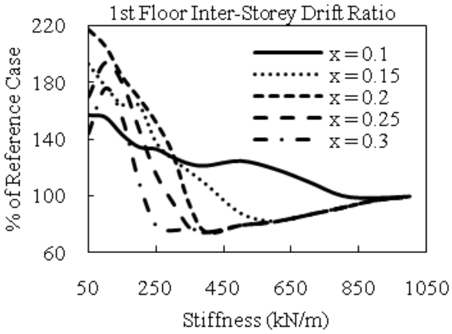

Figure 5 – 1st floor inter-storey drift ratio for varying stiffness and clearance distance

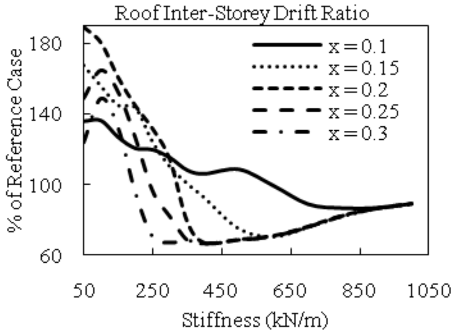

Figure 6 – Roof inter-storey drift for varying isolator stiffness and clearance distance

3.2. DISPLACEMENT TIME HISTORY

Figure 7 shows the displacement time history of the roof of an IC model using a bearing stiffness of 400 kN/m and a clearance of 0.25 metres versus the RC. At particular instances the IC's displacement was greater than the RC however the peak displacement of the IC, a primary indicator of structural damage was significantly lower than the RC. Furthermore, Figure 8 and Figure 9 show the displacement and inter-storey drift envelopes for the IC and RC. These curves plot the maximum displacements and inter-storey drift ratios for each storey and clearly show the superiority of the IC. The displacement time history of the isolated floor slab for three ground motion records is also provided in Figure 11. For all records, the absolute maximum displacement of the slab was much less than the clearance size of 0.25 metres shown by the thick horizontal lines. Hence, the slab did not collide with the adjacent column and the overall response of the structure was subsequently improved.

This is in contrast to Figure 10, the displacement time history of the roof of an IC model with a bearing stiffness of 200 kN/m and a clearance of 0.15 metres. Although the floor was isolated from the beams, the response of the IC was greater than that of the RC at numerous points. Furthermore, the maximum displacement of the IC model was 0.57 metres, larger than the RC at 0.38 metres. Hence these parameters increased rather than decreased structural response.

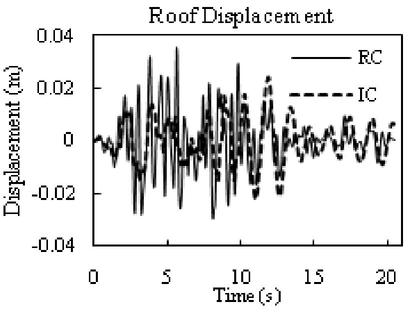

Figure 7 – Roof displacement time history. (400 kN/m, 0.25 metre clearance)

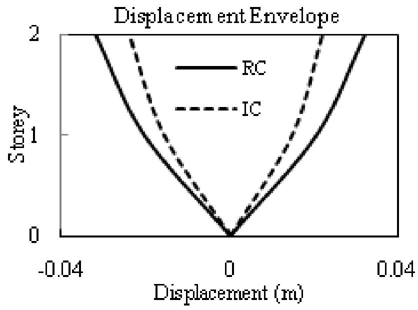

Figure 8 – Displacement envelope (400 kN/m, 0.25 metre clearance)

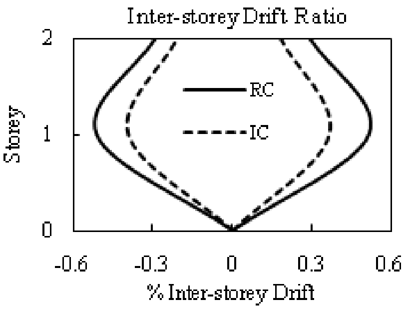

Figure 9 – Inter-storey drift ratio (400 kN/m, 0.25 metre clearance)

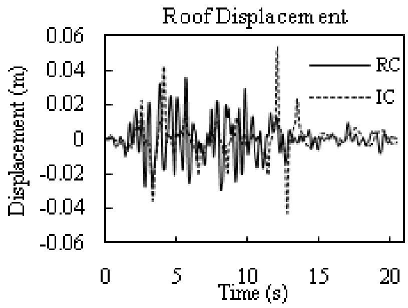

Figure 10 – Roof displacement time history (200 kN/m, 0.15 metre clearance)

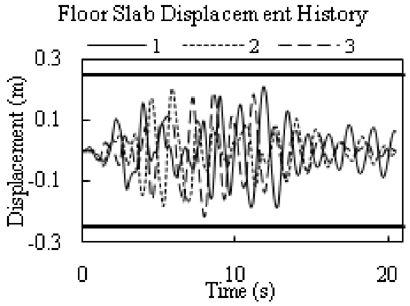

Figure 11 – Floor slab displacement time history (400 kN/m, 0.25 metre clearance)

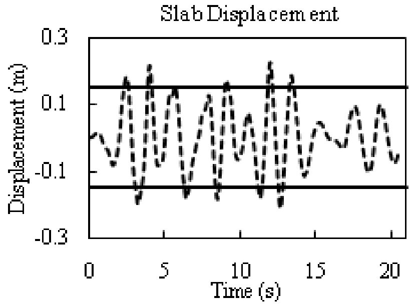

Figure 12 – Floor slab displacement time history (200 kN/m, 0.15 metre clearance)

Examining Figure 12, the floor slab displacement of this particular model, provides some explanation of this behaviour. The maximum displacement of the slab was significantly greater than the clearance distance, defined by the two horizontal lines at ±0.15 metres, at numerous times. As such, collisions between the slab and adjacent columns occurred frequently, imposing additional loads on the primary frame and decreasing the isolation system's effectiveness. At the instances when the roof displacement of the IC exceeded that of the RC (Figure 10), the displacement of the floor slab was also greater than the clearance distance. These results suggest that a strong correlation may exist between controlling the slab displacement and the performance of the isolation system.

3.3. BASE STOREY SHEAR & OVERTURNING BASE MOMENT

Figure 13 shows the base storey shear force of the IC as a percentage of the RC. When the bearing stiffness was very low, the shear force of the IC was substantially greater than the RC. Base shear then decreased with increasing bearing stiffness until 250 – 350 kN/m and then began to increase again as the bearing stiffness became increasingly large and the bearing connections became rigid. For a clearance size of 0.3 metres and bearing stiffness of 300 kN/m, the IC experienced 30% of the base shear force that the RC did.

Additionally the overturning base moment imposed on the IC as a percentage of the RC is shown in Figure 14. The IC experienced 40% of the overturning base moment that the RC did when the clearance distance was 0.3 metres and the bearing stiffness was 270 kN/m. Again, when the bearing stiffness was low both indicators were amplified due to additional loads imposed by slab-column pounding effects. Thus it seems important to control the clearance size and bearing stiffness to mitigate slab-column impact loads and utilise the isolation system effectively.

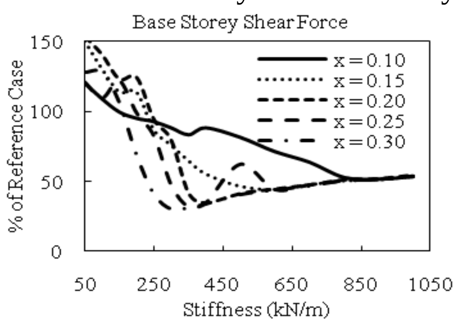

Figure 13 – Base storey shear force

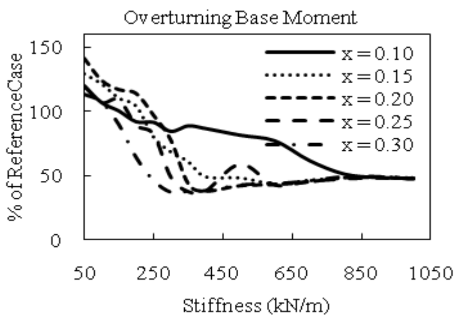

Figure 14 – Overturning base moment

3.4. MODE SHAPES

The mode shapes of a structure provide an indication of the deformation expected to occur for various forcing frequencies and loading combinations. Since changes in column size, storey height and other variables affect the natural frequency of a structure it was expected that changes in the stiffness and clearance size of the isolation system would also affect the frequency of the system.

Table 3 contains the frequency and period of the first two modes of an IC model with a clearance of 0.2 metres. Mode 1 exhibited a large variation in modal frequency whereas the variation was minimal for mode 2, suggesting that mode 1 was the dominant structural mode. This analysis was conducted for a range of clearance sizes and the results were consistent to 3 decimal places; the frequency of the system was virtually independent of the clearance between the floor slab and adjacent column. Figure 15 compares the mode shapes for the RC and IC models. For mode 1, the IC has a significantly smaller amplitude than the RC. Since this was the dominant structural mode and thus most likely to occur, this reduced amplitude of deformation would be beneficial.

		Mode 1		Mode 2	
		f (Hz)	T (s)	f (Hz)	T (s)
Reference Case		2.25	0.45	7.43	0.13
Isolated Cases	k = 50	0.26	3.87	3.79	0.26
	k = 100	0.36	2.75	3.81	0.26
	k = 150	0.44	2.26	3.82	0.26
	k = 200	0.51	1.96	3.83	0.26
	k = 250	0.57	1.76	3.85	0.26
	k = 300	0.62	1.62	3.86	0.26
	k = 350	0.66	1.50	3.87	0.26
	k = 400	0.71	1.41	3.89	0.26

Table 3 – Frequency and period of modes 1 and 2 for isolated and reference cases

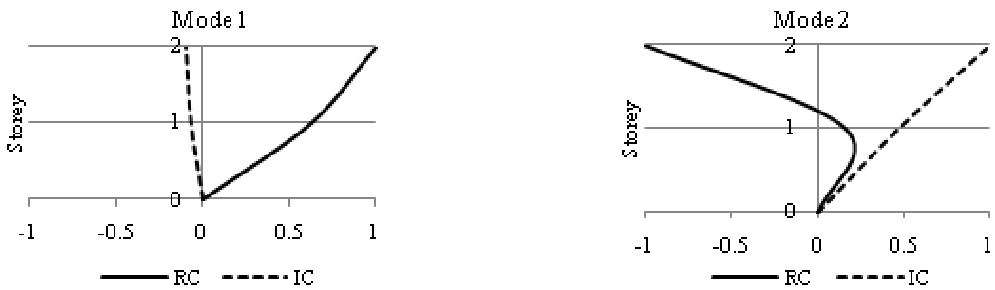

Figure 15 – Mode shapes

3.5. ENERGY DISSIPATION

Figures 14 – 17 contain plots of the kinetic energy and the viscous, external and static work done by the RC and IC models during the ground motions. A range of clearance sizes were investigated and a consistent trend emerged, thus the results shown are for a clearance of 0.3 metres only. The kinetic energy (Figure 16) of the RC is shown by the solid black line on the right hand axis whilst the energy within the IC is shown by the broken line on the left hand axis. Using 100 kN/m bearings, the kinetic energy oscillated from 0 in the troughs to 23 kNm at the peaks. These values were 10 times greater than the range produced for the RC, implying a greater amount of kinetic energy within the IC due to floor slab oscillations. The minimum kinetic energy occurred when the floor slab displacement was maximum whilst the peaks occurred when the displacement was minimum as the slab oscillated through its original position.

The viscous and external work curves (Figure 17 and Figure 18) further illustrate the benefits of floor slab isolation. For all stiffness values, the cumulative work done by buildings with isolated floors was substantially greater than that of the RC, suggesting that IC structures had the capacity to do a greater amount of work and therefore dissipate more seismic energy than the structures without. Since the IC and RC were identical in all aspects except the isolation mechanism, it holds that the favourable energy dissipation characteristics were primarily due to the isolation mechanism.

Finally, the static work curves are given in Figure 19, again with the RC shown on the right hand axis and the IC on the left hand axis. Static work provides an indication of the work done by static resisting forces within the system and the structure containing an isolated floor did seven times more static work than the RC did. Furthermore, the maximum static work done was greatest when the bearing stiffness was minimum, however due to the constraints imposed by pounding, a balance must be struck between energy dissipation and excessive retarding pounding forces.

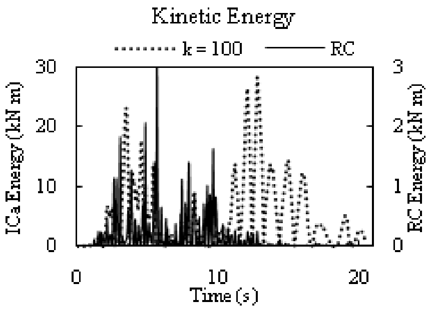

Figure 16 – Kinetic energy

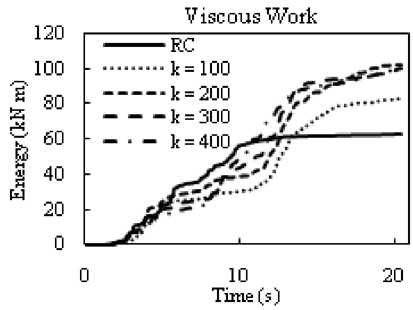

Figure 17 – Accumulated viscous work

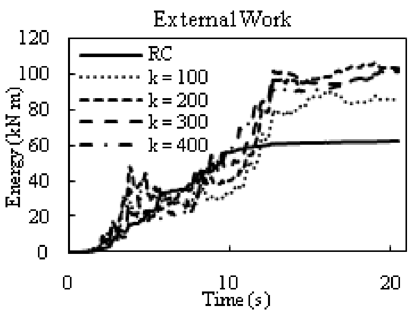

Figure 18 – Accumulated external work

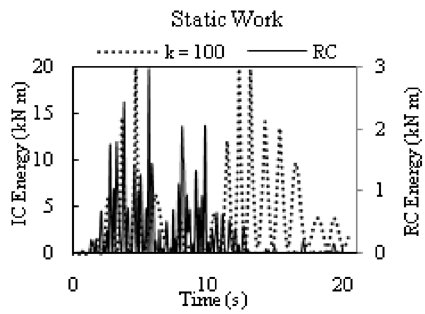

Figure 19 – Static work

3.6. MODULAR JOINT PAD IMPACT FORCE

Determining the force applied to the modular joints spanning the clearance between the slab and column was critical to ensure the column was not subjected to excessive impact forces when pounding occurs. Figure 20 shows the maximum force experienced by the modular joints as a function of the bearing stiffness for various clearance distances. When the stiffness was very low, the impact force was significantly large and could cause damage to the face of the column despite the protection provided by the modular joint. Alternatively as the bearing stiffness increased, the impact forces decreased as the frequency of slab-column pounding reduced.

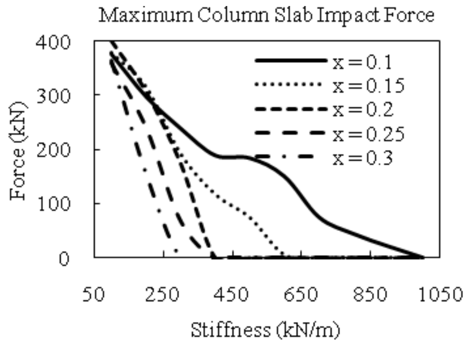

Figure 20 – Column – slab impact force

4. CONCLUSION

Isolating the floor slab from the supporting beam can provide significant improvements in structural response compared to traditional fixed floor structures providing the properties of the isolation mechanism are suitably optimised. Of primary importance is the stiffness of the rubber isolation bearings and the clearance distance between the edge of the floor slab and the adjacent column. The inter-storey drift ratio for the roof of the IC structure was 32% less than that of the RC when the bearing stiffness was 400 kN/m and the clearance was 0.2 metres. Similar results were obtained using larger clearance distances and smaller bearing stiffness values.

The base storey shear and the overturning base moment results provide further support to this proposal. Base shear was reduced by 70% whilst the overturning base moment decreased by 60% when the floor slab was isolated from the primary frame compared to the RC. Additionally, the principal modes shapes and the energy dissipation curves for the IC model clearly show the benefits of the isolation mechanism.

However, when the bearing stiffness was too low or the clearance distance was too small, the response of structures fitted with an isolated floor mechanism was amplified. This was primarily due to adverse effects caused by pounding between the floor slab and the adjacent columns. As shown by the inter-storey drift, shear force or overturning moment analyses, once pounding was eliminated either by using stiffer bearings or by increasing the clearance distance, the structural response of IC frames was significantly less than that for fixed floor structures. Analysing the forces imposed on modular joints support this and provides a useful means for establishing when pounding ceases to occur.

Overall, the initial numerical results of this research suggest that isolating the floor slab from the beams could prove a useful means of dissipating seismic energy in structures. Further research is required, particularly concerning the localised effects of pounding, installation and the application and performance of this mechanism in other structures such as steel frames and multi-storey buildings. However the significant improvements in structural response achieved suggest that this proposal could represent a viable solution to reduce seismic loading effects on structures.

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