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The influence of different concrete classes on the seismic response of a seismically isolated building

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ABSTRACT

In this study, an eight story seismically isolated building representing a mid-rise type building was employed to investigate the effect of usage of different concrete classes (C20, C25, C30, C40, and C50) on the seismic response of a seismically isolated building. The prototype fixed base buildings were converted to seismically isolated buildings by introducing rubber isolators at base level. Analyses were conducted by using two different isolation systems (QW5Tb3 and QW10Tb3).The modelling of conventional fixed base prototype seismically isolated buildings and their modal analyses were conducted on finite-element program SAP2000, whereas, modelling of seismically isolated buildings and nonlinear time-history analyses were conducted using 3D-BASIS program. Floor accelerations, Story shears and inter-story drift ratios were the key structural responses considered. The analysis results showed concrete strength have significant effects on the seismic behaviour of the structures. Seismically isolated buildings with isolation system having 5% characteristic strength, C40 and C50 concrete buildings showed less first floor accelerations as compared to the lower concrete class buildings. In addition, isolated buildings with C40 and C50 concrete showed much more inter-story drift ratio values at each floor level as compared to isolated buildings with C20, C25 and C30 concrete which showed values very close to one another.

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1. Introduction

Reinforced concrete structures make up most of the existing structure stock in the world because of their high rigidity, long service life and high resistance to earthquake damage. Analysis of these structures for different levels of earthquake intensity and for determination of damage levels is a matter of high priority in earthquake prone areas (Erdem, 2016). Many studies have been conducted on the dynamic behaviour and seismic vulnerability of reinforced concrete structures (Verderame et al., 2010; Rojman and Fajfar, 2009; Golghate et al., 2013; Peruš et al., 2013).

One of the important factor that affects evaluation of the seismic performance of existing building is the concrete compressive strength (Pereira and Romao, 2016a; 2016b). In the literature review, a number of research studies have been performed for investigating the influence of concrete strength on the structural performance. A recent work by Coskan et al. (2015) demonstrated performance limits, structural stiffness, deformation quantities, ultimate bearing capacity and plastic hinge processed are strongly affected by the concrete strength. In another study, Bayraktar et al. (2014) investigated 90 reinforced concrete buildings that were collapsed during 2011 Van Earthquake to determine the overall structural performance of the building. It was found that 47 % of the buildings have an average compressive strength between 8 and 12 MPa, 26% of the buildings have an average compressive strengths between 4 and 8 MPa, and 20 % of the buildings have average compressive strengths between 12 and 16 MPa. In parallel, Erberik (2008) and Kocak (2005) have made similar observations on the influence of concrete strength quality on the earthquake

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performance after Duzce Earthquake (1999) and Marmara Earthquake (1999), respectively. The results showed that the poor compressive strength adversely affected the overall structural behaviour.

Reinforced concrete structures in many civil engineering applications can often be subjected to short duration dynamic loadings generated from earthquakes. Under such circumstance, it is obvious that structures with high ductility is much more desirable. It has been observed from previous research (Hwang and Hsu, 2000; Madden et al., 2002; Pant and Wijeyewickrema, 2012) that ideally, base-isolation is an effective technique to improve the seismic performance of buildings. Although base isolation decreases the possibility of damage (less inter-story drifts, shear forces and floor accelerations) of a building, it causes to large displacements in the structure relative to the ground. This, in turn, increases the potential of impact or pounding of a building with adjacent structures (Pant and Wijeyewickrema, 2012).

A review of the literature indicates that in contrast to seismic behaviour of seismically isolated reinforced concrete buildings, no study has been conducted so far to investigate the effect of usage of different concrete classes on the seismic response of a seismically isolated building. In this study, an eight story seismically isolated building representing a mid-rise type building was employed to investigate the effect of usage of different concrete classes (C20, C25, C30, C40, and C50) on the seismic response of a seismically isolated building. Analyses were conducted by using two different isolation systems (QW5Tb3 and QW10Tb3). Floor accelerations, story shears and inter-story drift ratios were the key structural responses considered.

2. Methodology

In this study, an eight story seismically isolated building representing a mid-rise type building was employed to investigate the effect of usage of different concrete classes on the seismic response of a seismically isolated building. The prototype building makes use of a moment resisting frame structural system. The building was symmetric in plan with dimensions of 25m x 25m and consists of 5 bays in both *X* and *Y* principal directions. The typical story height was 3m. It was assumed that the building importance factor was 1, and that the soil type according to UBC 97 was Class C. Regarding loading on the buildings, story masses were usually used which are lumped at centre of gravity (at master joint). A translational mass of 500 kNs^2/m was assumed to be lumped at the centre of mass of each floor. Typical floor plan and 3D view of the building in question are shown in Figs. 1 and 2, respectively. *X*-sectional dimensions of column and beam elements of the building changes with the concrete class used. Figure of frame sections of 8 story building using C20 concrete is shown Fig. 3. There was not a drastic or considerable variation of sizes as concrete compressive strength increases. For example, the size of square columns with C50 concrete was 52 cm while with C20 it was 60 cm. In proportioning of the load bearing structural elements i.e. beams and columns according to concrete class employed, important points of the building codes like strong column - weak beam concept and shear capacity at beam-column connection region were taken into account. The prototype fixed base buildings were converted to seismically isolated buildings by introducing rubber isolators at base level (also called base isolation).

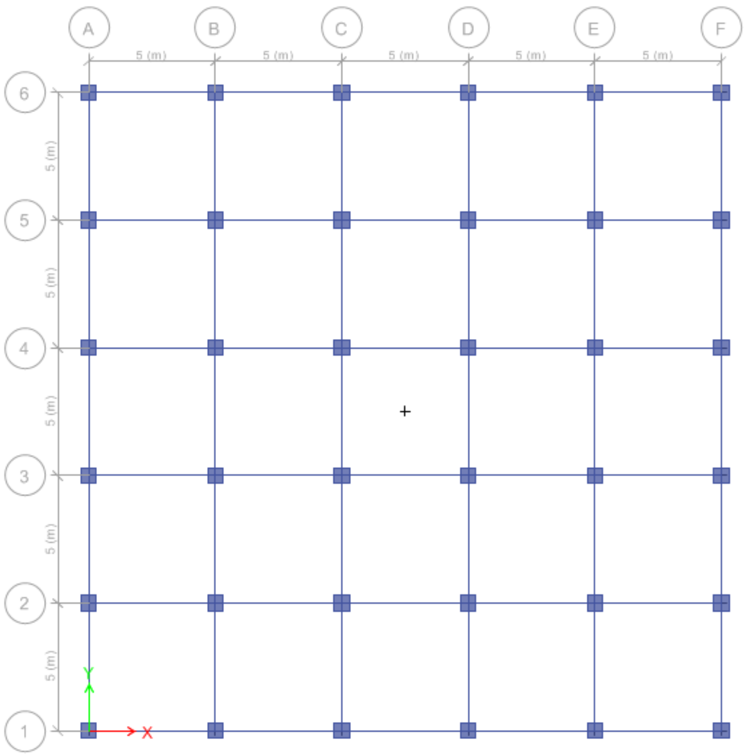

Fig. 1. Typical floor plan of prototype 8 story building.

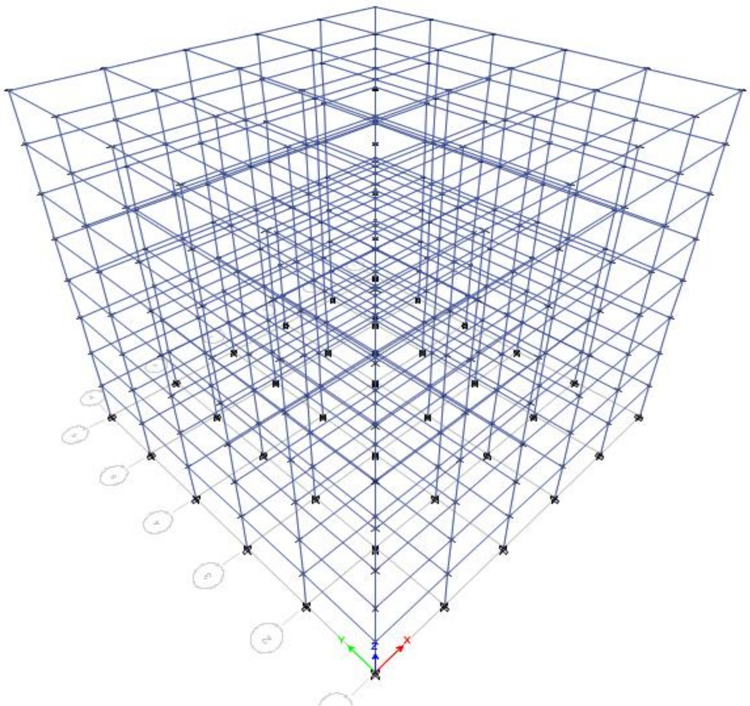

Fig. 2. 3D view of prototype 8 story building.

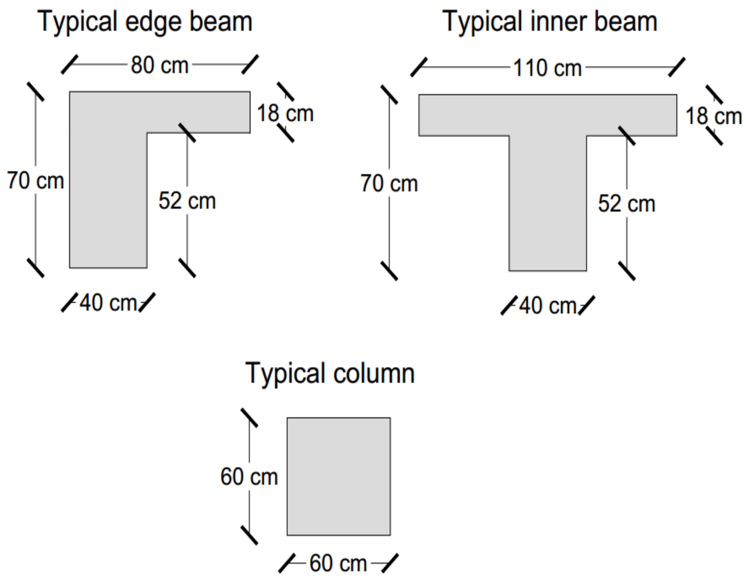

Fig. 3. Details of the frame section of the building with C20.

The modelling of conventional fixed base prototype seismically isolated buildings and their modal analyses were conducted on finite-element program SAP2000, whereas, modelling of seismically isolated buildings and nonlinear time-history analyses were conducted using 3D-BASIS program which has been particularly developed, by Nagarajaiah et al. (1991), for nonlinear dynamic analysis of three dimensional base isolated structures. The fundamental/first mode periods of 8 story fixed base buildings with different concrete classes were obtained through modal analyses and are presented in Table 1. As compressive strength increased modulus of elasticity increased but size of frame section (especially columns) decreased resulting in less moment of inertia. The increase in elasticity modulus was not so significant as compared to the decrease in section sizes resulting in decrease in stiffness and in turn resulting in increase in period. In addition to, the values of spectral acceleration (SA) was small (in the range of 0.01 -0.02 g) as the period of the buildings was about 3 s. A ground motion record from 1994 Northridge earthquake was used for nonlinear time-history analyses and was taken from NGA database which is an updated version of PEER's strong ground motion database. Analyses were done by using bidirectional earthquake input with strong component of earthquake along one main axis (*X*-axis) and weak component of earthquake along other orthogonal main axis (*Y*-axis) of the buildings.

The acceleration time history and spectrum record for acceleration used in the analysis are shown in Fig. 4. It should not be forgotten that the spectrum shows the responses of a single degree freedom system. As the building was a multi degree of freedom system, the response will vary.

Table 1. Fundamental/First mode period of prototype fixed base building.

Concrete Class	Period (s)	SA (g)
C20	0.521	0.33
C25	0.573	0.29
C30	0.638	0.24
C40	0.729	0.19
C50	0.843	0.13

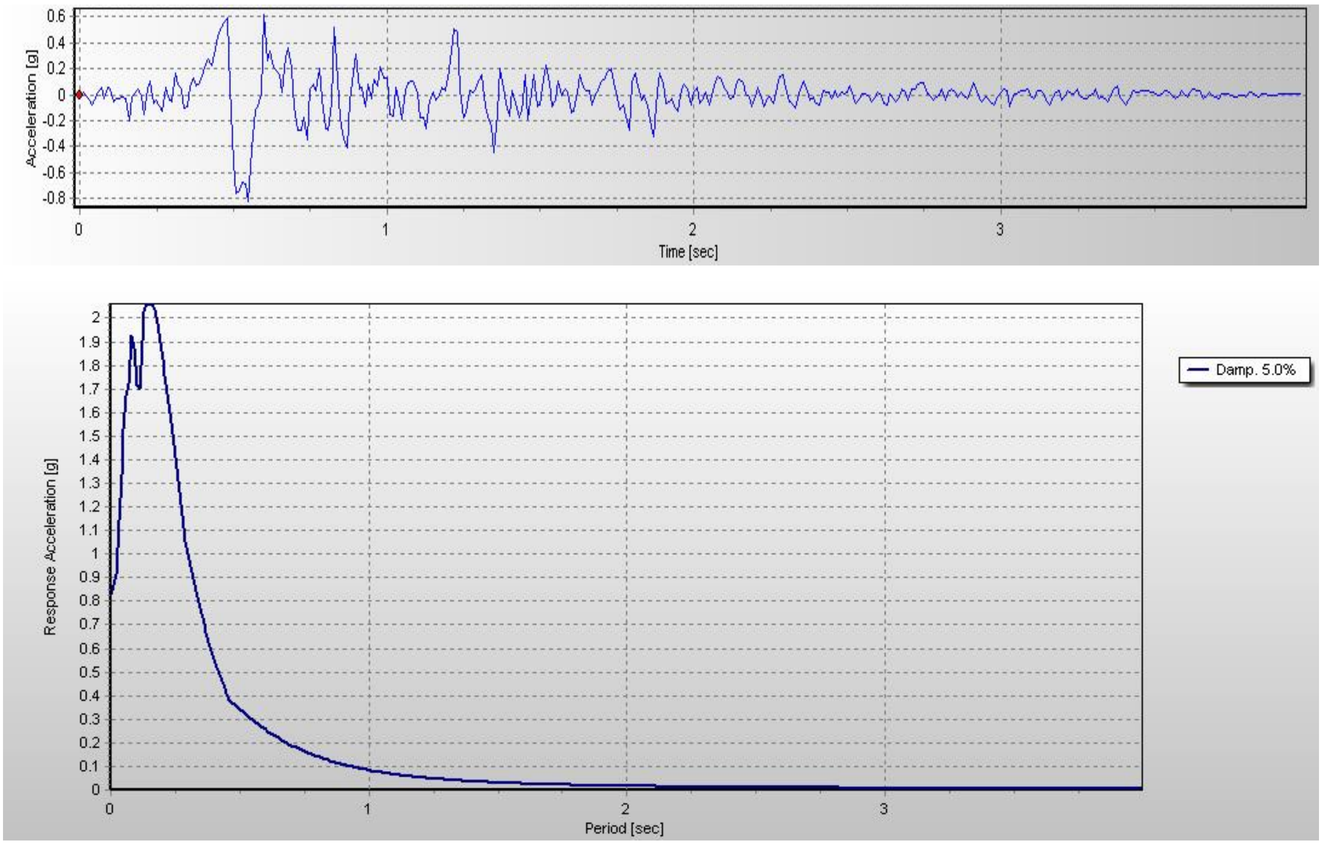

Fig. 4. Acceleration time history and spectral acceleration used.

A translational mass of 500 kNs²/m was assumed to be lumped at the centre of mass of each floor. Each floor had 3 degrees of freedom i.e. 2 translations and 1 rotation. Rigid diaphragm was introduced at each floor level to distribute the lateral forces to structural elements of the frame. Analyses were realized by using two different isolation systems (QW5Tb3 and QW10Tb3). Here, in QW5Tb3 isolation system QW5 indicates characteristic strength of isolation system normalized with weight of the building (*W*) to be 5% and Tb3 indicates isolation period to be 3 seconds. It is worth-mentioning that characteristic strength of the isolation system is a measure of level of damping in the isolation system. The parameters concerning isolation systems were summarized in Table 2. To calculate parameters for each isolator, *Q* (characteristic strength), *K1* (pre-yield stiffness), *K2* (post-yield stiffness), and *Fy* (Yield force) should be divided by total number of isolators used in the isolation system. In Table 2, α is post-yield to pre-yield stiffness ratio and *Dy* is yield displacement of isolation system. A constant value of 0.015 m was adopted for both the isolation systems.

3. Results and Discussion

As the seismically isolated buildings in this study are subjected to bi-directional earthquake excitations, the structural responses in both global *X* and *Y* direction have been considered for performance comparison. It is important to mention that the building models used in this study are symmetrical so the results obtained would be same if the axes are reversed. Moreover, the displacements at the isolation level or the base displacements obtained from the analyses of all the building models with similar isolation parameters are almost same so the main focus of attention for this study is the superstructure responses. Floor accelerations, Story shears and inter-story drift ratios are the key structural responses considered.

Table 2. Parameters related to modelling of nonlinear isolation system.

Isolation System	*Tb* (s)	*Q*/*W* (%)	*Q* (kN)	*K2* (kN/m)	*K1*(kN/m)	α (*K2*/*K1*)	*Dy* (m)	*Fy* (kN)
QW5Tb3	3	5	2207.3	19739.209	166889.2	0.118	0.015	2503.34
QW10Tb3	3	10	4414.5	19739.209	314039.2	0.063	0.015	4710.59

3.1. Floor accelerations

Floor accelerations in global X-direction or X-axis of the buildings, with characteristic strength level of 5% for the isolation system, are shown in Fig. 5. It was evident that as it was moved from the base towards the top floor, no particular increasing or decreasing trend (either linear or nonlinear) was observed for any concrete class. However, it was seen that variation in accelerations become more pronounced as the increased compressive strength of the concrete i.e. the building with concrete class C20 showed less variation in accelerations as it was moved from the base towards the top floor as compared to the building with concrete class C50 which showed significant changes in acceleration at each floor level. The top floor acceleration was more or less same in all the buildings. On the other hand, first floor accelerations with the buildings having C20, C25 and C30 concrete were almost same but the buildings employing C40 and C50 concrete class showed less first floor accelerations as compared to the aforementioned buildings. Moreover, in all cases top floor accelerations were more than the first floor accelerations as expected.

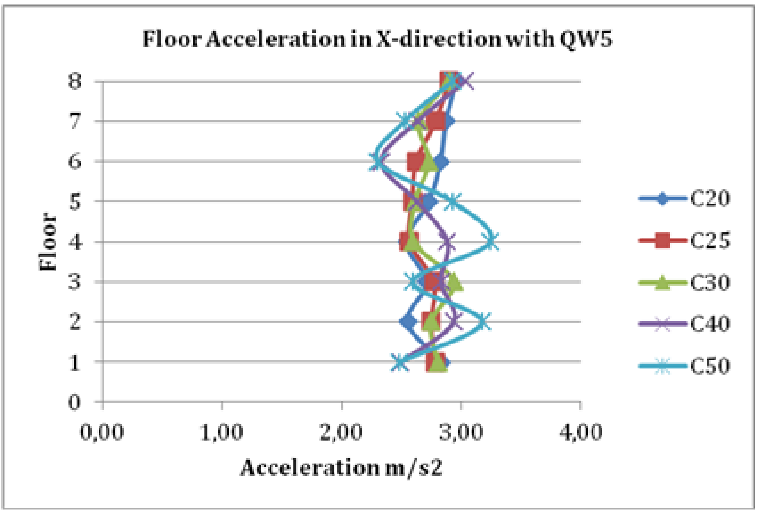

Fig. 5. Floor acceleration in *X*-direction with QW5.

Floor accelerations in global Y-direction with the isolation system having characteristic strength of 5% are shown in Fig. 6. In this case, buildings with concrete class C25 and C30 showed more and less similar trend as it was moved from first floor towards the top floor. However, all the buildings i.e. with C20, C25, C30, C40, C50 showed similar increasing acceleration trend in the upper floors. Top floor accelerations in all cases were more than the 1st floor accelerations with C40 and C50 showing more accelerations at the top floor as compared to others. C40 and C50 buildings were indeed showing more acceleration at every floor level. It was conjectured that the relatively higher top floor accelerations of the building with C40 and C50 could be attributable to the reduction in the number of plastic hinges that were occurred in the columns.

As can be seen in Fig. 7, with the increase in characteristic strength of the isolation system i.e. at 10% characteristic strength or in other words with the increase in damping of the isolation system, the variations in accelerations become much more prominent even for the lower concrete classes i.e. C20, C25, C30 etc. The top floor accelerations were not same either as shown in Fig. 4. As it was moved from 6th to 8th floor an increasing trend of accelerations is observed for all the buildings. Like seismically isolated buildings with isolation system having 5% characteristic strength, C40 and C50 concrete buildings showed less first floor accelerations as compared to the lower concrete class buildings.

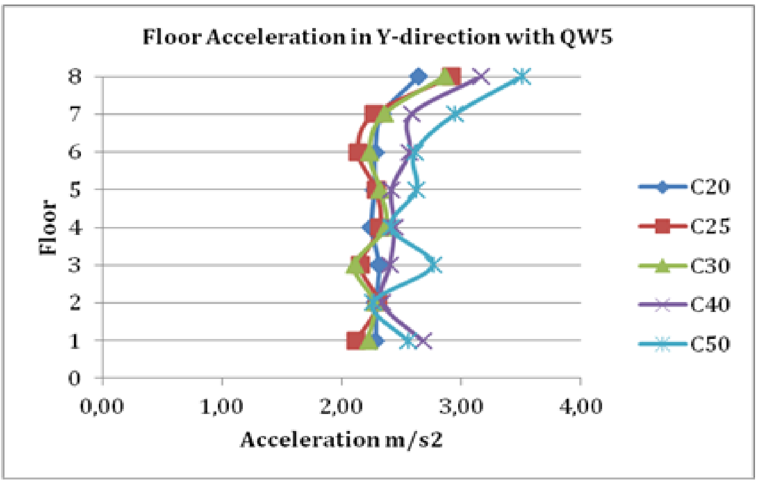

Fig. 6. Floor acceleration in *Y*-direction with QW5.

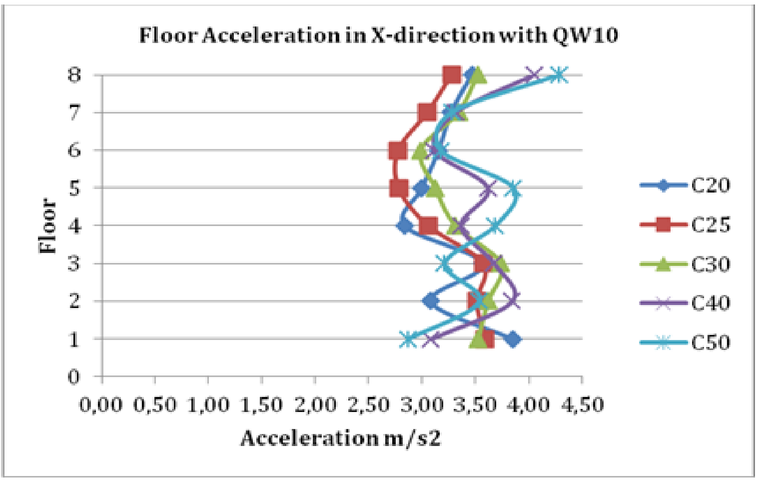

Fig. 7. Floor acceleration in *X*-direction with QW10.

With the characteristic strength of the isolation system of 10%, the floor acceleration pattern in *Y*-direction is presented in Fig. 8. A sharp increase in accelerations for upper floors i.e. 6th to 8th could be clearly seen in the figure.

For all the cases considered, in general the mid floor levels were seen to be the most suitable for housing the equipment or machinery sensitive to vibrations as these floor levels experience less accelerations compared to others. Upper floors have been found to be the least favourable choice for vibration sensitive equipments.

3.2. Story shears

Story shears in X and Y directions, for all the 8 story buildings obtained with isolation system having 5% characteristic strength, are presented in Figs. 9 and 10, respectively. For all the buildings with different concrete classes similar trend of (more or less linearly) decreasing shears has been observed (as we move from base towards top floor). Seismically isolated buildings with concrete C40 and C50, however, showed slight deviation from C20, C25, and C30 in both directions. Moreover, base shear values were almost same for all of the buildings in question.

With isolation system of characteristic strength 10%, though shear values are higher, the trend of shear in *X*-direction was approximately same as of 5% characteristic strength with very small variation observed at lower and mid floor levels (Fig. 11). At this strength level, base shear values were also almost same for all the buildings as evident in Fig. 7. However, if it was looked at the shears in *Y*-direction there was a clear difference in trend at upper floor levels as compared to *X*-direction but the trend is same for all the buildings i.e. buildings with concrete C20, C25, C30, C40, and C50 follow the same trend (Fig. 12).

3.3. Inter-story drift ratios

At characteristic strength level of 5%, all the buildings follow the same inter-story drift ratio trend in both *X* and *Y* directions as can be seen in Figs. 13 and 14, respectively. The inter-story drift ratios first increased then decreased which was again followed by an increase and a decrease in values with the lowest value observed for the top floor level (as we move from base towards top floor). Although the trend was same for all the concrete buildings, the buildings with C40 and C50 concrete showed slightly higher values at each floor level (building with C50 in particular). In fact, a sharp increase of drift ratios was seen at 2nd and 4th floor levels especially.

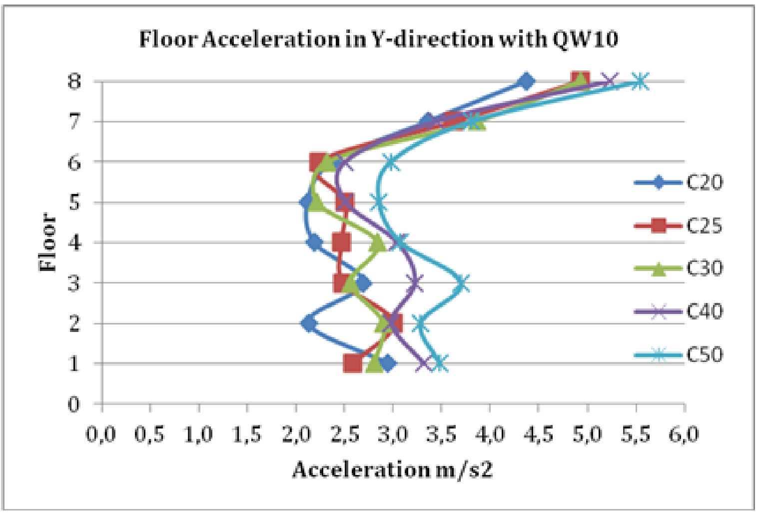

Fig. 8. Floor acceleration in *Y*-direction with QW10.

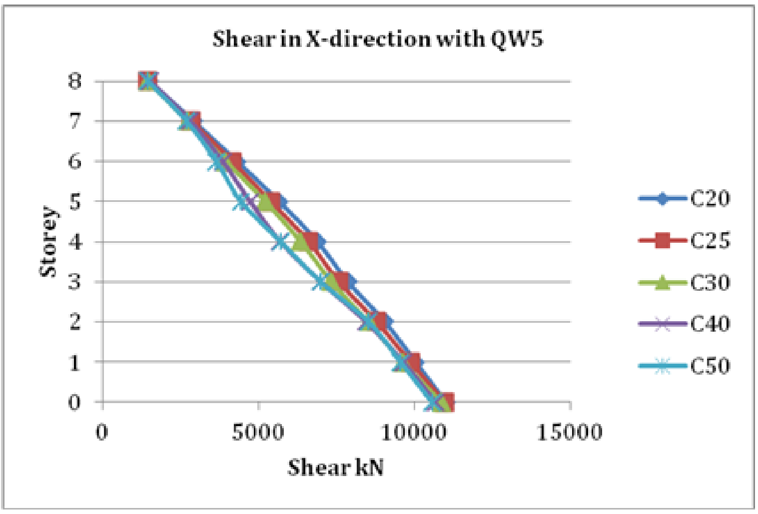

Fig. 9. Story shears in *X*-direction with QW5.

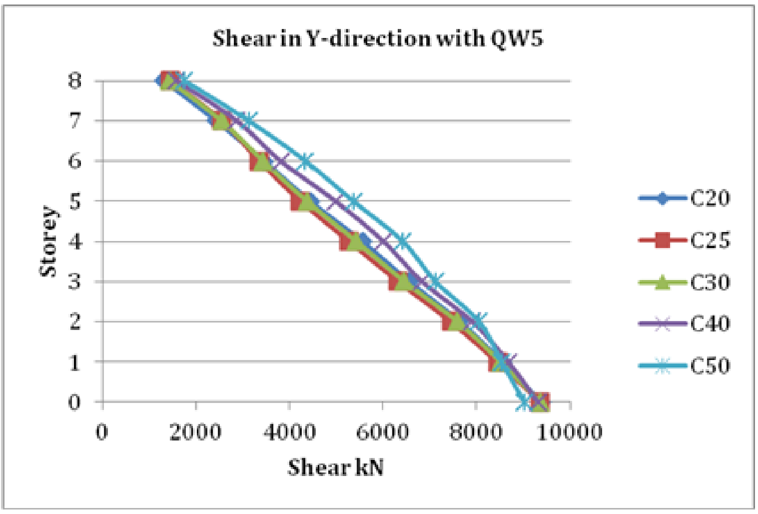

Fig. 10. Story shears in *Y*-direction with QW5.

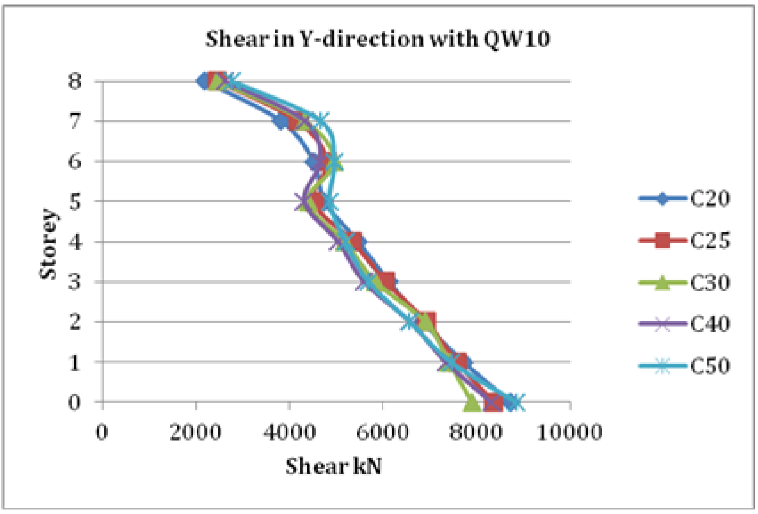

Fig. 11. Story shears in *Y*-direction with QW10.

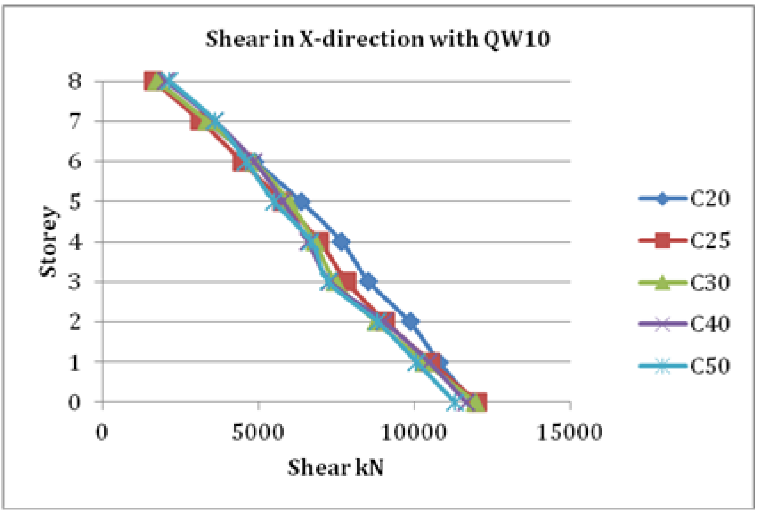

Fig. 12. Story shears in *Y*-direction with QW10.

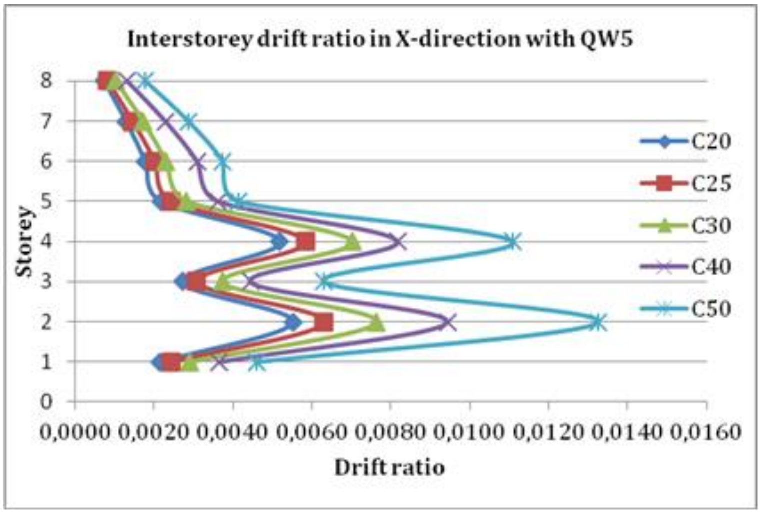

Fig. 13. Inter-story drifts in *X*-direction with QW5.

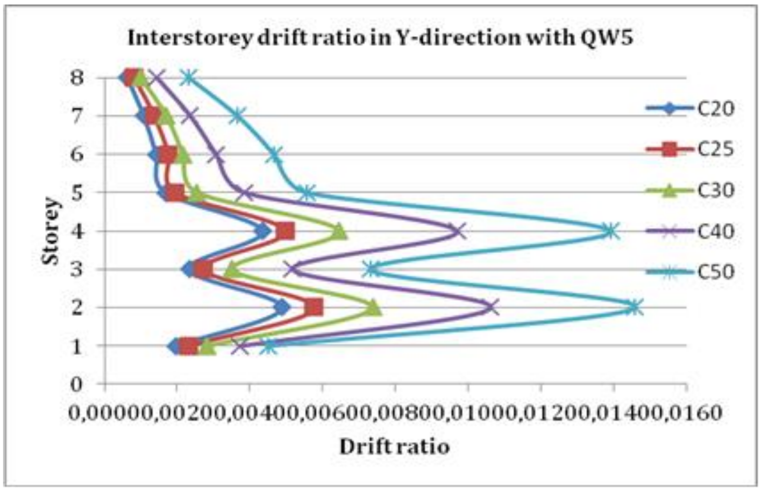

Fig. 14. Inter-story drifts in *Y*-direction with QW5.

With the characteristic strength level of 10%, the overall trend for all buildings remains the same as seen with 5% characteristic strength level. But here isolated buildings with C40 and C50 concrete showed much more inter-story drift ratio values at each floor level as compared to isolated buildings with C20, C25 and C30 concrete which showed values very close to one another. A sharp increase in inter-story drift ratios at 2nd and 4th floor levels for buildings with C40 and C50 was clearly evident in Figs. 15 and 16. This probably reflects the fact that there was more deformation on local vertical members accompanied with destructive tensile strains during the dynamic loading.

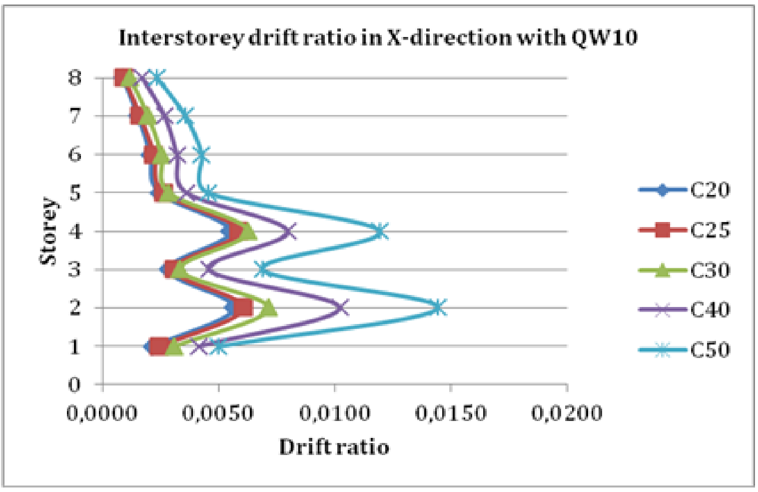

Fig. 15. Inter-story drifts in *X*-direction with QW10.

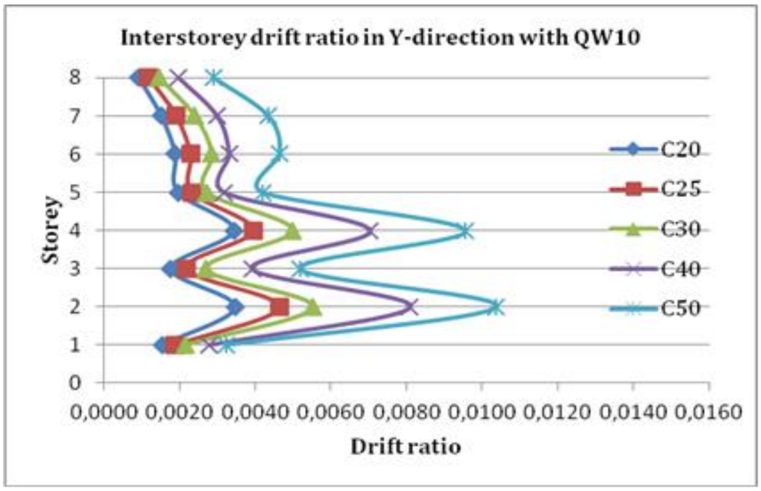

Fig. 16. Inter-story drifts in *Y*-direction with QW10.

4. Conclusions

Concrete strength have considerable effects on the earthquake behaviour of the seismically isolated structures. Floor accelerations, story shears and inter-story drift ratios were significantly affected by the concrete strength class. In general for all the cases considered, buildings with C50 concrete exceeds the maximum inter-story drift ratio limit imposed by UBC at 2nd and 4th floor (with R=1). In fact, buildings with C40 concrete also exceeds the inter-story drift ratio limit in some cases. Inter-story drifts beyond a certain level may be dangerous for the integrity of the building. For all the cases considered, in general the mid floor levels are seen to be the most suitable for housing the equipment or machinery sensitive to vibrations as these floor levels experience less accelerations compared to others. Upper floors have been found to be the least favourable choice for vibration sensitive equipments. With isolation system of characteristic strength 10%, there is a clear difference in trend at upper floor levels for the shear values in Y-direction as compared to X-direction but the trend is same for all the buildings with concrete C20, C25, C30, C40, and C50 follow the same trend. In a future research study, effects of concrete strength on the seismic response of seismically isolated RC buildings which has irregular geometrical configurations should be investigated.

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