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THE EFFECTS OF CONCRETE STIFFNESS AND STRENGTH ON THE SEISMIC RESPONSE OF REINFORCED CONCRETE FRAME BUILDINGS

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ABSTRACT. This paper is concerned with the effects of concrete material properties on the seismic response of reinforced concrete frame buildings. In particular, the influence of concrete stiffness and strength on the dynamic seismic response of RC buildings is assessed. A series of nonlinear dynamic time-history analyses of model RC frame buildings are conducted. A range of concrete stiffness and strength are examined and under a number of earthquakes of different amplitude, duration and frequency content.

It is shown that concrete stiffness is more dominant factor affecting the dynamic seismic response of reinforced concrete structures than concrete strength. Moreover, it is shown that the direction of the applied earthquake motion also affects the dynamic response of the framed building, especially in cases of irregular structures with differential stiffness in different directions. It is also observed from the response spectra that the applied seismic load resonates with the dominant mode of building vibration in the direction of the applied seismic load. This may suggest that real recorded earthquake motions from instrumented concrete buildings may be processed to identify their dynamic modal characteristics.

Keywords: Earthquake, Reinforced Concrete, Framed Buildings, Strength, Stiffness

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INTRODUCTION

The vast majority of new residential and commercial buildings constructed nowadays are made of reinforced concrete (RC) frames. Many such structures are located in areas characterised by moderate seismicity and therefore need to be designed according to established seismic design standards (e.g. Eurocode 8) (Elnashai & Di Sarno, 2008).

Seismic design codes provide guidelines for structural/geotechnical analysis methods, consideration of structural frame topology, lateral load support systems, interaction between the structure and the ground, interaction and pounding between adjacent structures etc. (Dowrick, 2009). Due to the transient nature of earthquakes which impose cyclic loads on structures, an important aspect of seismic design is the selection and use of appropriate materials that are able to perform well under such cyclic loading and provide adequate ductility (Newmark & Rosenblueth, 1971). Material damping, stiffness and strength are key parameters that may affect the seismic performance of a structure and therefore need to be carefully evaluated in seismic structural design.

This paper presents a numerical study related to the effect of different material properties on the seismic response of RC framed structures. A model RC moment-resisting frame structure behaving in a nonlinear manner is considered and is analysed using dynamic time-history analysis. Several aspects of material behaviour are considered, including both aspects of stiffness and strength for both the steel reinforcement and the concrete material. This study shows that the seismic response of RC frame structures can be severely affected by some material properties, whereas it can be rather insensitive to some other parameters. The results of this work may be useful in assessing the influence of construction imperfections on the desired designed response of a RC structure.

LITERATURE REVIEW

Significant progress has been made over the last 6 decades in the field of earthquake engineering. Seismic analysis and design of buildings (Paulay & Priestley, 1992; Elghazouli, 2016), dams (Gazetas, 1987; Pelecanos, 2013; Pelecanos et al., 2013, 2015, 2016, 2018), bridges (Sextos & Pitilakis, 2003) and other infrastructure is now well established. Various methods of seismic analysis have been proposed and widely used for the seismic design of a large number of structures, including equivalent static (Elghazouli, 2016), pushover analysis, modal analysis (Chopra, 1995), response spectrum analysis (Swensen & Wong, 2011) and dynamic time-history analysis (Nassar & Krawlinker, 1991), incremental dynamic analysis (Vamvatsikos & Cornell, 2002), each one offering different opportunities but also associated with different limitations and requirements. Also, seismic design considerations have considered different structural arrangements such as Moment-Resisting Frames (MRF), Concentrically Braced Frames (CBF), Eccentrically-Braced Frames (EBF), shear walls, central cores etc. (Elghazouli, 2016).

Moreover, several aspects of seismic structural response have been investigated. It has been shown that significant effects on the seismic response of structures may originate from a sequence of multiple earthquakes (Hosseinpour & Abdelnaby, 2017), near-fault earthquakes (Chopra & Chintanapakdee, 2001; Hatzigeorgiou, 2010), higher mode structural vibration (Paulay & Priestley, 1992; Maniatakis et al., 2013), soil-structure interaction (Priestley & Park, 1987; Mylonakis & Gazetas, 2000; Allotey & Naggar, 2008). The seismic response of

RC structures has been of particular importance and a wealth of literature is now available (Kappos & Penelis, 2014).

FINITE ELEMENT MODEL

A three-story, two-bay 3D RC frame structure is modelled using the nonlinear finite element program SeismoStruct 2018 (Antoniou & Pinho, 2004). The RC frame is subjected to static loads (dead and variable loads, considering combinations according to Eurocode 2) as well as dynamic loads (imposed seismic accelerations at all the foundation nodes). The geometry of the considered structure is shown in Figure 1. Both the steel reinforcement and the concrete material of all the beams and columns are modelled with cyclic nonlinear constitutive models, as shown in Figure 2. For the steel reinforcement, the Menegotto-Pinto steel model material (#stl_mp) is adopted which is a uniaxial steel model initially programmed by Yassin (1994) based on a simple, yet efficient, stress-strain relationship proposed by Menegotto and Pinto (1973), coupled with the isotropic hardening rules proposed by Filippou et al. (1983). For the concrete, the Mander et al. nonlinear concrete model (#con_ma) is adopted, which is a uniaxial nonlinear constant confinement model that follows the constitutive relationship proposed by Mander et al. (1988) and the cyclic rules proposed by Martinez-Rueda and Elnashai (1997). The confinement effects provided by the lateral transverse reinforcement are incorporated through the rules proposed by Mander et al. (1988), whereby constant confining pressure is assumed throughout the entire stress-strain range.

All beams and columns are modelled using the Inelastic force-based frame element type (infrmFB). This is the force-based 3D beam-column element type capable of modelling members of space frames with geometric and material nonlinearities. The sectional stress-strain state of beam-column elements is obtained through the integration of the nonlinear uniaxial material response of the individual fibres in which the section has been subdivided, fully accounting for the spread of inelasticity along the member length and across the section depth. Nonlinear dynamic time-history analysis (DTHA) is performed using direct integration of the equations of motion using the Hilber-Hughes-Taylort (HHT) method (Hilber et al., 1977) with the alpha factor equal to zero.

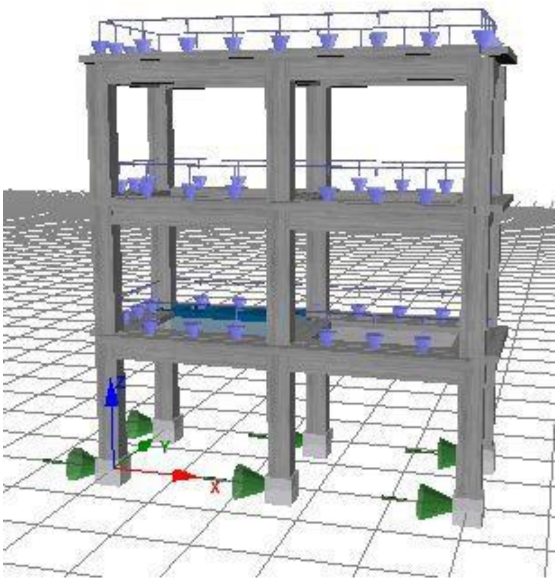
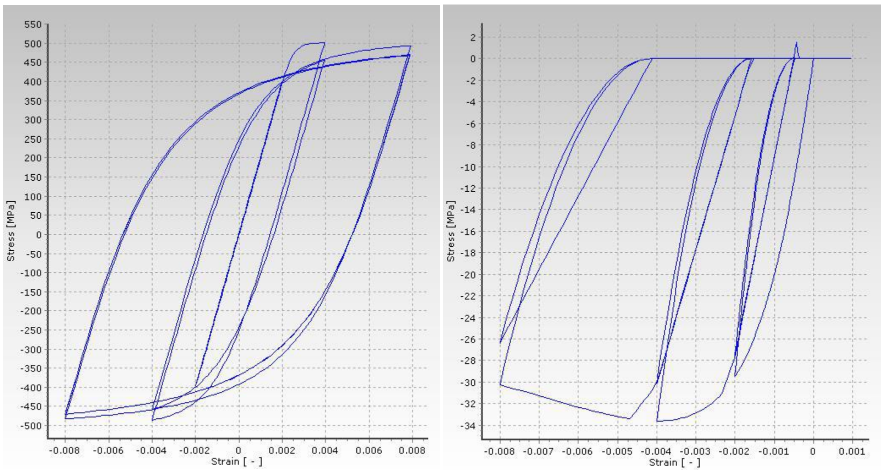


Figure 1 Geometry of the FE model



(a) (b)

Figure 2 Material models for: (a) steel reinforcement (#stl_mp), (b) concrete (#con_ma).

A number of DTHA was run with different material properties. In particular, different combinations of stiffness (assessed through the small-strain Young Modulus, Eo) and strength (assessed through the ultimate normal strength, σo) were considered, as listed in Table 1. Case 1 is the reference case.

Table 1. Material properties of the considered types of frames.

No	**Case**	**Reinforcement**		**Concrete**	
		Young Modulus, E [kPa]	**Yield strength, σ [kPa]**	**Young Modulus, E [kPa]**	**Yield strength, σ [kPa]**
1	E_o, σ_o	2.0 E+8	500 000	2.487 E+7	28 000
2	2 E_o, σ_o	4.0 E+8	500 000	4.974 E+7	28 000
3	0.5 E_o, σ_o	1.0 E+8	500 000	1.244 E+7	28 000
4	E_o, 2 σ_o	2.0 E+8	1000 000	2.487 E+7	56 000
5	E_o, 0.5 σ_o	2.0 E+8	250 000	2.487 E+7	14 000

Two real earthquake ground motions are used as input, which have different intensity, duration and frequency content, as listed in Table 2. These are the Imperial Valley, US (1979) and Kocaeli, Turkey (1999) earthquakes, of which the acceleration time-histories are shown in Figure 3 along with the corresponding response spectra. It is shown for the latter figure that the Kocaeli earthquake has very high frequency content, whereas the Imperial Valley earthquake has low frequency content with large spectral ordinate values for long periods. It is considered that the use of these two distinct earthquake motions is useful in investigating different aspects of the seismic response of the considered structure.

Table 2. Input EQ acceleration records.

No	**Earthquake**	**Location**	**Date**	**Duration [s]**	**PGA [g]**
EQ1	Imperial Valley	Imperial Valley, US	15/10/1979	39.49	0.32
EQ2	Kocaeli	Kocaeli, Turkey	17/08/1999	34.97	0.35

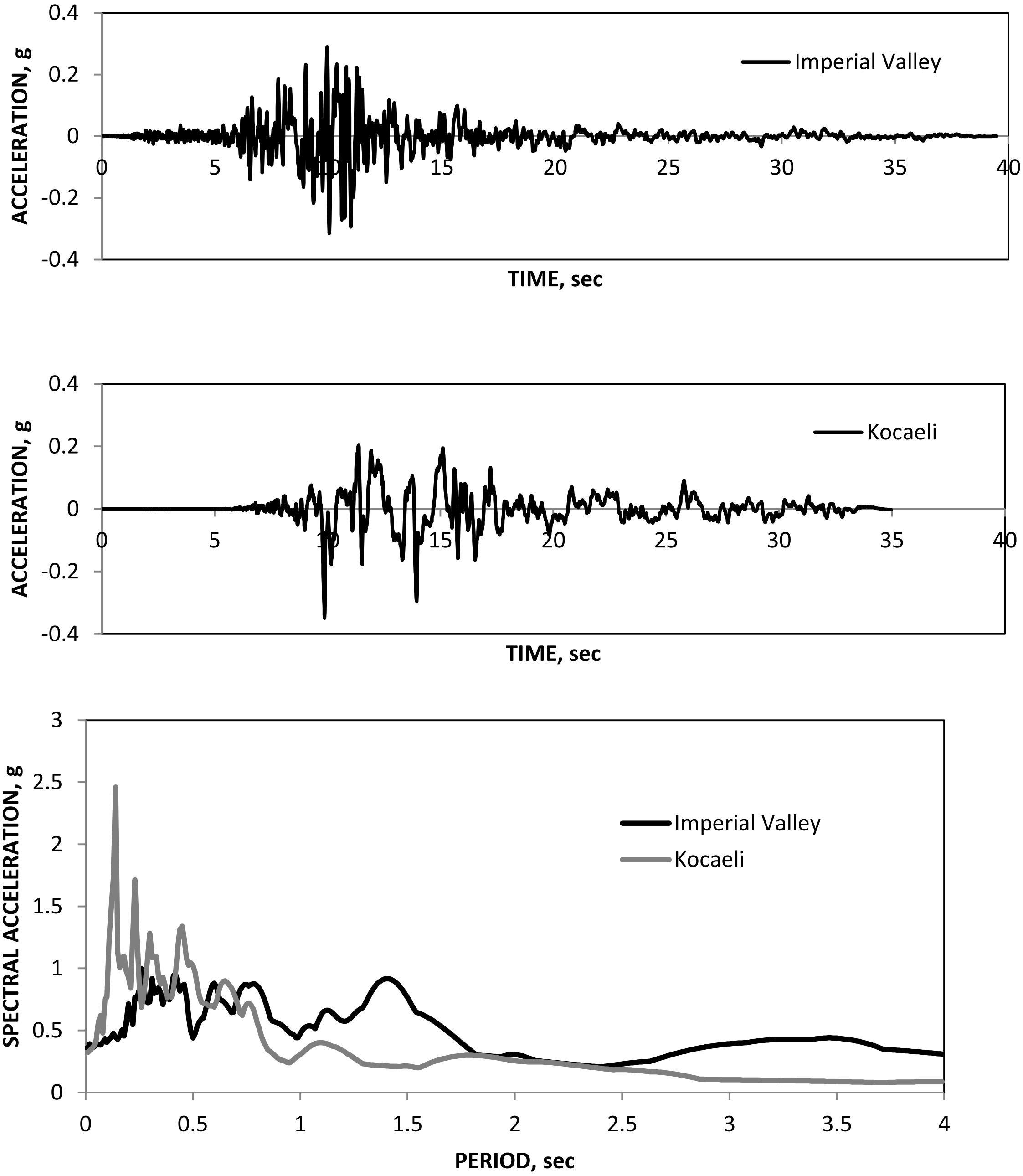


Figure 3 EQ Input acceleration motions (a) Imperial Valley, (b) Kocaeli, (c) response spectra.

COMPUTATIONAL RESULTS

A number of DTHAs is run according to the details described in Section 3 before. Figures 4 and 5 show the response spectra of the calculated acceleration response at the top of the structure for earthquake input motions of the Imperial Valley and Kocaeli earthquakes, respectively.

From these figures it is shown that, as expected, changing the stiffness of the materials has a significant effect on the spectral response of the structure and therefore it is observed that cases 2 and 3 with the different stiffness provide considerably different frequency content. Moreover, it is observed that the changes in strength also provide some difference in the spectral response of the structure, but this is noted to be to a lesser extent. This is because cases 4 and 5 with the different strength, although exhibit some differences in the dynamic behaviour, these are smaller than those from the different stiffness.

Also, it is worth noting that when comparing the two earthquake input motions it is observed that the latter case of the Kocaeli earthquake appears to result in significantly higher spectral ordinates. This is believed to be due to the high frequency content of the input motion which appears to be closer to the fundamental frequency of vibration of the structure and therefore lead to phenomena of resonance.

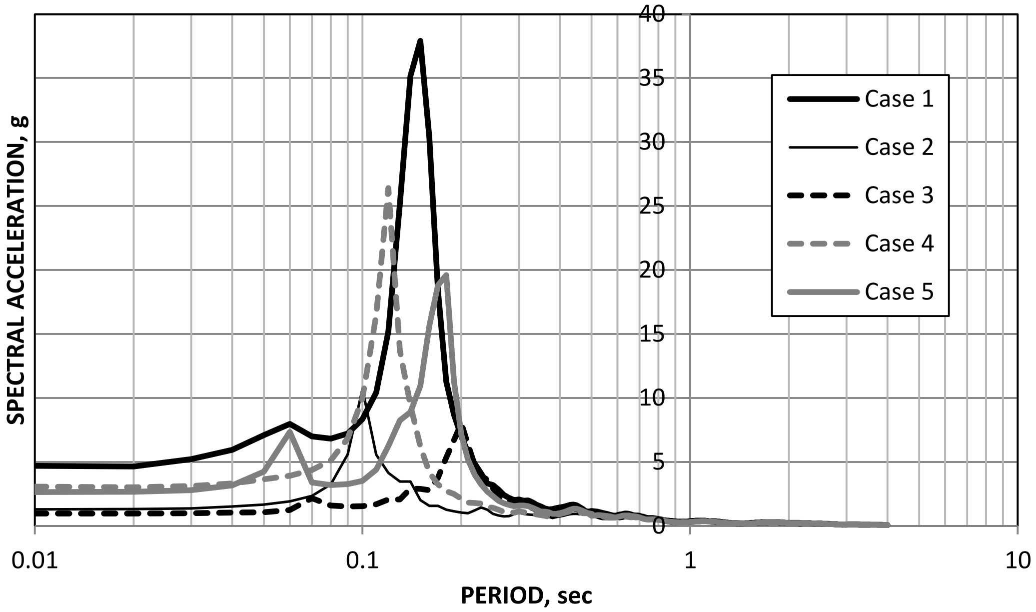


Figure 4 Response Spectra for EQ1: Imperial Valley

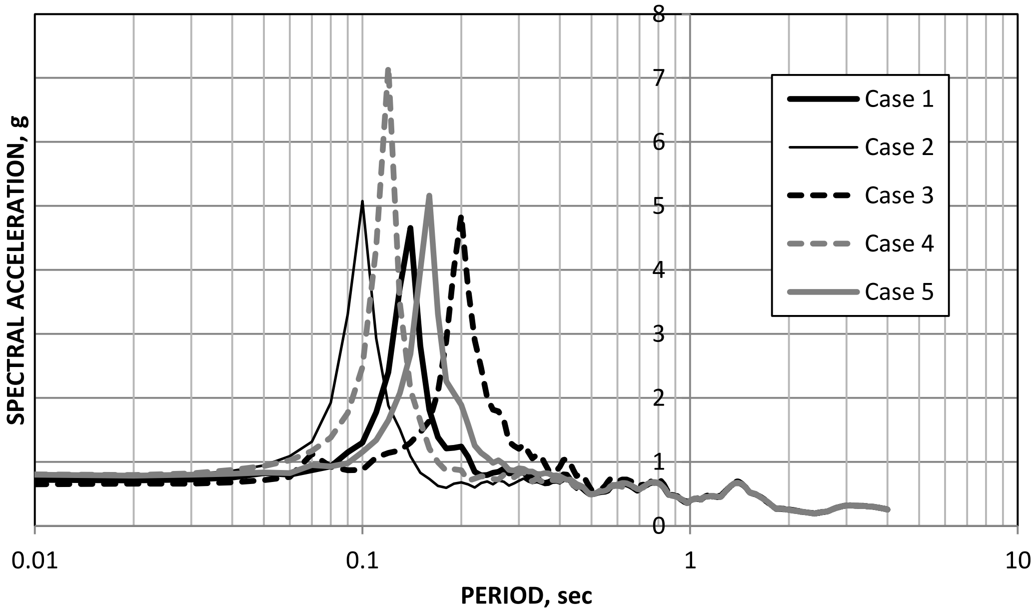


Figure 5 Response Spectra for EQ2: Kocaeli

Moreover, Table 3 lists the fundamental periods of the RC structure, as these were obtained from a modal (eigenvalue) analysis (Chopra, 1995) and from the DTHA (i.e. from the peak ordinates of the response spectra of the two considered earthquakes). It is firstly shown that there is an excellent agreement between the frequency-domain (modal) analysis and the time-domain (DTHA) analysis. This suggests that processing of the results of a time-domain analysis is able to identify the dominant frequencies (or periods) of vibration of a structure. It should be noted that there are some minor differences in the modal and DTHA fundamental period values, and the pattern is consistent, i.e. the DTHA provides slightly larger values of fundamental period which may be attributed to the fact that the DTHA is nonlinear and therefore there is softening of the structural response and thus period elongation.

Also, it is again confirmed that changes in the stiffness have a more pronounced effect on the seismic structural response than changes in the strength of the materials, as the latter yield smaller changes in the fundamental period of vibration of the structure.

Table 3. Predicted fundamental periods of vibration

Case	Fundamental Period [sec]		
	Modal	Response Spectrum	
		Imperial Valley	Kocaeli
1	0.135	0.15	0.14
2	0.096	0.10	0.10
3	0.191	0.20	0.20
4	0.116	0.12	0.12
5	0.157	0.18	0.16

CONCLUDING REMARKS

This study aims to investigate the effects of different material properties on the seismic response of RC frame structures. It follows a numerical approach in which a series of dynamic finite element analyses of a model structure case study are performed for different values of various materials properties and under two earthquakes of different intensity, duration and frequency content. Nonlinear dynamic time-history analyses and modal (eigenvalue) analyses are carried out to investigate the effects of material properties.

It is shown that stiffness properties of the concrete and steel reinforcement have a more pronounced effect on the seismic structural response than the strength properties. Also, it is shown that nonlinear dynamic time-history analyses are able to provide estimates of the fundamental periods of vibration of the structure, as the latter quantities compare very favourably with those from a modal frequency-domain analysis.

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