ASSESSMENT OF STRUCTURES SUBJECTED TO MULTIPLE EARTHQUAKES

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SUMMARY:
The basic approach for design of infrastructure components and systems utilizes a single loading scenario and a single performance criterion; usually life-safety. In recent years, social and economic considerations have necessitated that more than one performance criterion is used, and also more than one level of earthquake intensity. This multiple load-and-limit state seismic design is the current best practice. There are a few locations around the world that warrant an alternative approach. These locations are affected by more than one earthquake within a relatively short period of time due to their special seismo-tectonic setting. Currently, the response of engineering structures to multiple earthquakes that impose strong ground shaking is at a very early stage of development. There are no parameterized solutions that predict the effect of several strong earthquakes on buildings and bridges. Indeed, all papers in the published literature assume that the first earthquake will impose the maximum damage.
The present analytical work deals with assessment of structures subjected to seismic sequences. In so doing, inelastic constant ductility acceleration, displacement and force reduction factor spectra are derived for a set of natural multiple earthquakes. Advanced hysteretic models with stiffness and/or strength degradation are employed to simulate the seismic response of typical non-compliant reinforced concrete (RC) structures under earthquake loading. Normalized strength ratio spectra for the selected set of records indicate that the force demand on structures may be three times that of a single event. Such demand is significantly influenced by the ductility levels, especially for periods greater than 1.0 second. Consistently higher inelastic displacements have been observed for multiple earthquakes than the case of a single event, even when the latter was the strongest record of the sequence.

Keywords: multiple earthquake, response modification factor, stiffness degradation, strength deterioration

1. INTRODUCTION

Survey carried out in the aftermath of several seismic swarms world-wide have been showing that moderate magnitude earthquakes may be followed by aftershocks with comparable or even higher magnitude. Evidence may be found, for example, in assessing the strong motions recorded in California (Northridge 1994), Italy (L'Aquila, 2009), Japan (Tohoku, 2011), New Zealand (Darfield, 2010; Christchurch, 2011) and Turkey (Duzce, 1999; Kocaeli, 1999). As a result, there is a great deal of ongoing research aimed at investigating the effects of seismic sequences on the structural response of new and existing buildings and bridges. Pioneering studies were carried out in the US by Mahin (1980) and Aschheim and Black (1999). Such studies were primarily focused on the nonlinear response analysis of single-degree-of-freedom (SDOF) systems subjected to the mainshock–aftershock acceleration time histories. The results of the analyses showed that the displacement ductility demand of elastic-perfectly plastic SDOF systems slightly increases at the end of the main aftershock with respect to the mainshock. Elnashai *et al*. (1998) observed that the ductility demand required by multiple earthquake ground motions can be remarkably higher than that required by a single event. This finding was confirmed lately by extensive analytical work carried out by several researchers on simplified SDOF systems and multi-storey framed buildings, either in steel or reinforced concrete (RC). For example, Amadio *et al*. (2003) and Fragiacomo *et al*. (2004) analyzed the effects of repeated natural and artificial earthquakes on the response of nonlinear SDOF models and steel moment

resisting frames. The results of the parametric analyses demonstrated that the response of such systems is influenced chiefly by natural structural periods of vibration of the system, type of ground motion and level of displacement ductility.
More recently, comprehensive analytical studies have been carried out on a large ensemble of as-recorded main shock and aftershock acceleration time histories to investigate the effects of repeated earthquakes on inelastic displacement ratios and hence on the maximum inelastic displacements of SDOF systems (Hatzigeorgiou and Beskos, 2009; Hatzigeorgiou, 2010-a, 2010-b). Nevertheless, the hysteretic model used for the nonlinear dynamic analyses relies on an elasto-plastic (bilinear) constitutive relationship in which the unloadings and subsequent loadings are assumed to be parallel to the original loading curve; strain hardening or softening takes place after yielding initiates. Further studies have also been carried on multi-storey steel (Ruiz-Garcia and Negrete-Manriquez, 2011) and reinforced concrete (Hatzigeorgiou and Liolios, 2010) plane framed structures subjected to sequence of real and artificial multiple earthquakes. Such studies are aimed at establishing whether or not damage indices, expressed in terms of peak and residual displacements and the force reduction factors, are affected by afore, main and after-shocks. The outcomes of the above analyses on SDOF systems and plane frames are two-fold and they influence both force- and displacement-based schemes currently employed in seismic design and assessment. On one hand, multiple earthquakes enhance remarkably the displacement demands in comparison with single seismic events. Thus, inelastic displacement ratios may be increased by 100% or more with respect to that obtained for the counterpart single earthquakes. On the other hand, seismic sequences lower the force reduction factors. As a result, modern displacement-based design and assessment procedures should be revised, as they rely primarily on the reliable estimate of the inelastic displacement demand. Additionally, force-based procedures, as implemented currently in several codes of practice world-wide, should be reassessed to achieve safe seismic structural design. The present analytical study discusses the preliminary results of an ongoing research aimed at investigating the effects of multiple earthquakes on the inelastic response of structural systems. In the following sections, inelastic constant ductility spectra are examined, alongside force reduction factor spectra.

2. STRONG MOTION RECORDS

The earthquake records from the 2011 off Pacific coast Tohoku (Japan) seismic event have been utilized in the present study to derive the inelastic response spectra and to perform the nonlinear dynamic analyses on the RC framed system used as a benchmark structure. The Tohoku earthquake was a magnitude Mw=9.0 undersea mega-thrust earthquake that occurred on 11 March 2011 off the coast of Japan, with epicenter approximately 70kms east of the Oshika Peninsula of Tohoku and the hypocenter at an underwater depth of approximately 32kms (e.g. Takewaki *et al*., 2011). Following the main quake of March 11, there has been a large number of moderate-to-high magnitude after-shocks. By 10 August 2011, Japan experienced over 900 aftershocks, with about 60 of them aftershocks being over magnitude Mw=6.0 and three over magnitude Mw=7.0.
The accelerograms of the 2011 Tohoku earthquake are downloaded from the database of K-Net available on the website (http://www.k-net.bosai.go.jp/k-net/quake/index_en.html). Five seismic stations are selected to represent a set of sites subjected to multiple earthquakes of varying magnitudes and source-to-site distances. The sample acceleration time histories were firstly corrected employing a linear baseline correction and a Butterworth band-pass filter (Freq1=0.1 Hz, Freq2=25 Hz, Order 4). The properties of the suite of sample records are summarized in Table 1. The North-South components of the ground strong motions were utilized. From the tens of records captured at five seismic sites, three are selected for each site to represent scenarios of leading and trailing strong-ground motions. A leading set is where the first earthquake has the largest peak ground acceleration (PGA) in the sequence of three (FKS016), while a trailing set has the second (IBR003 and MYG004) or third (FKS010) records as its highest PGA signal.
The frequency content of the afore-, main and after-shocks is measured by the predominant (T_p) and the mean (T_m) periods of the ground motions; the latter is the best simplified frequency content characterisation parameter (Rathje *et al*., 1998). The values of T_p and T_m are lower than 0.3 seconds; T_m is generally higher than T_p. It is observed that no direct correlations exist between the predominant

and mean period of the main shocks and the counterpart values of the afore- and after-shocks.

Table 1. – Seismic stations and earthquake records.

STATION		EARTHQUAKE								
Site	ID	Record ID	Lat.	Long.	Depth (km)	D_{ep} (km)	M_w	PGA (g)	T_p (sec)	T_m (sec)
Funehiki	FKS008	FKS008-1	37.20 N	141.66 E	27	118	6.1	0.229	0.120	0.142
		FKS008-2	37.36 N	141.28 E	27	77	6.0	0.279	0.200	0.199
		FKS008-3	37.42 N	141.32 E	27	110	6.1	**0.288**	0.080	0.119
Hirono	FKS010	FKS010-1	37.50 N	141.33 E	36	195	5.8	0.217	0.120	0.260
		FKS010-2	37.36 N	141.28 E	27	114	6.0	0.206	0.160	0.215
		FKS010-3	37.42 N	141.32 E	27	147	6.1	**0.756**	0.120	0.191
Shirakawa	FKS016	FKS016-1	38.10 N	142.86 E	24	100	9.0	**1.318**	0.080	0.192
		FKS016-2	37.50 N	141.33 E	36	64	5.8	0.113	0.080	0.185
		FKS016-3	37.36 N	141.28 E	27	66	6.0	0.097	0.120	0.137
Hitachi	IBR003	IBR003-1	37.50 N	141.33 E	36	41	5.8	0.278	0.100	0.200
		IBR003-2	36.11 N	141.26 E	43	28	7.7	**0.532**	0.100	0.159
		IBR003-3	37.42 N	141.32 E	27	35	6.1	0.100	0.100	0.144
Tsukidate	MYG004	MYG004-1	39.84 N	142.70 E	32	259	7.4	0.113	0.160	0.254
		MYG004-2	39.03 N	142.28 E	36	109	6.5	**0.230**	0.280	0.242
		MYG004-3	38.73 N	141.02 E	24	100	6.7	0.110	0.120	0.207

Key: D_{ep}= epicentral distance; M_w = moment magnitude T_p= predominant period; T_m = mean period.
The values of the peak ground acceleration for each seismic station are in bold.

The seismic sequence combinations considered for the nonlinear dynamic analyses carried out hereafter (*see* also Table 1) do not comply either with the empirical relation formulated by Omori (1984) or with the Gutenberg–Richter relationship (1954). The ratios of the PGAs for the sequence of three events suggested by Hatzigeorgiou (2010-a) cannot thus be used for the sample time histories of the 2011 Tohoku earthquake considered herein. Additionally, the records outlined in Table 1 were generated by different seismo-genetic faults. The selected accelerograms are, however, of high interest from the engineering seismology standpoint as they are representative of real earthquake records.

3. INELASTIC SPECTRA

Three piecewise hysteretic models were considered to evaluate the inelastic response spectra: the elastic-perfectly plastic, the elastic plastic with linear hardening and the modified Clough model (Clough and Johnston, 1966). The elastic plastic model is the simplest hysteretic model and can be employed to simulate the response of framed systems in which the plastic collapse is caused by the simultaneous onset (elastic-perfectly plastic) or the progressive formation (elastic plastic with hardening) of plastic hinges. However, the bilinear model does not account for cyclic degradation. The modified Clough model is thus utilized because it incorporates stiffness deterioration under reversal loading. In such a model, a bilinear curve serves as the primary envelope. To simulate degradation of stiffness, the reloading branches are aimed at the previous maximum response point. The slope of the reloading branch decreases as the maximum response increases. Three values of (post-yield) hardening were considered, namely 5%, 10% and 15%. An increase of the hardening value in the modified Clough model delays the amount of stiffness degradation.

Three values of constant ductility μ, namely 2, 4, and 6 were utilized. These ductility levels are commonly related to specific seismic damage states whether designing a new structural system or assessing an existing one in earthquake-prone regions (e.g. CEN, 2006-a; CEN, 2006-b; ASCE 41-6, 2007; ASCE 7-10, 2010; among others). The results presented hereafter focus primarily on the stiffness degradation model; the latter model can simulate the response of not-compliant reinforced concrete (RC) structures under earthquake loading. Such structures may experience severe damage under moderate-to-high magnitude seismic sequences due to the significant stiffness and strength degradation under reversal loads.

3.1 Acceleration response

The inelastic acceleration response spectra derived for the sequence of earthquake records with similar values of PGAs, i.e. the triad of time histories relative to Funehiki Station (FKS008), are provided in Figure 1. The computed results are for the stiffness degrading hysteretic model with 5% post-yield hardening. The response spectra for the single event refer to the first record in the sequence. The results are expressed in terms of spectral accelerations and spectral amplification factors. Figure 1 shows that the inelastic spectral demand for the multiple events is higher than that of the single record.

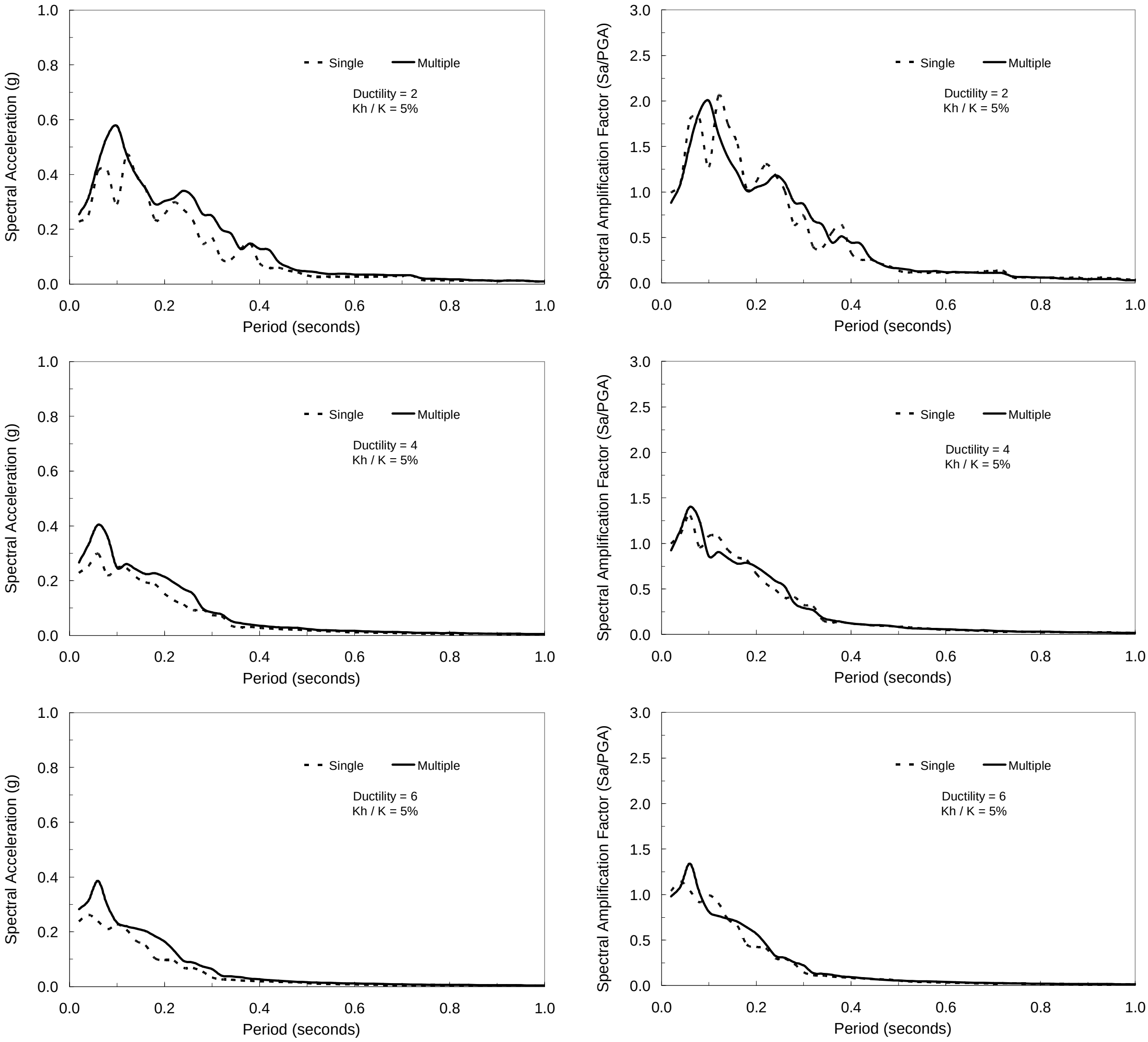

Figure 1. – Inelastic response spectra for ductility 2 (*top*), ductility 4 (*middle*) and 6 (*bottom*); Funehiki Station for the stiffness degrading hysteretic model with 5% hardening: spectral acceleration (*left*) and spectral amplification factors (*right*).

The maximum difference between single and multiple events is found at very low periods, i.e. less than 0.1 seconds. For μ=2, the inelastic spectral response for multiple records can be twice that relative to a single event (0.58g vs. 0.29g at 0.1 seconds). As the μ-value increases, the maximum difference is found for shorter periods: 0.6 seconds (for μ=4 and μ=6) vs. 0.1 seconds for μ=2. Moreover, the effects of sequence of earthquakes tend to become negligible for high ductile systems. Acceleration spectra estimated for high ductility and single event tend to match the response spectra for multiple earthquake records. It is also noted that multiple records spectra tend to be smoother than the single event counterparts. As a result, structures subjected to a main event and several aftershocks seem to be less sensitive to the frequency content of the input ground motion. The accumulation of local and global structural damage depends on the characteristics of the seismic motions. Few differences arise between the results derived for FKS008 and those estimated for the remaining sample stations considered for the present analytical work. Similar results were also computed for stiffness degrading hysteretic model with 10% post-yield hardening, as displayed in Figure 2 for seconds the case with μ=2 and μ=6.

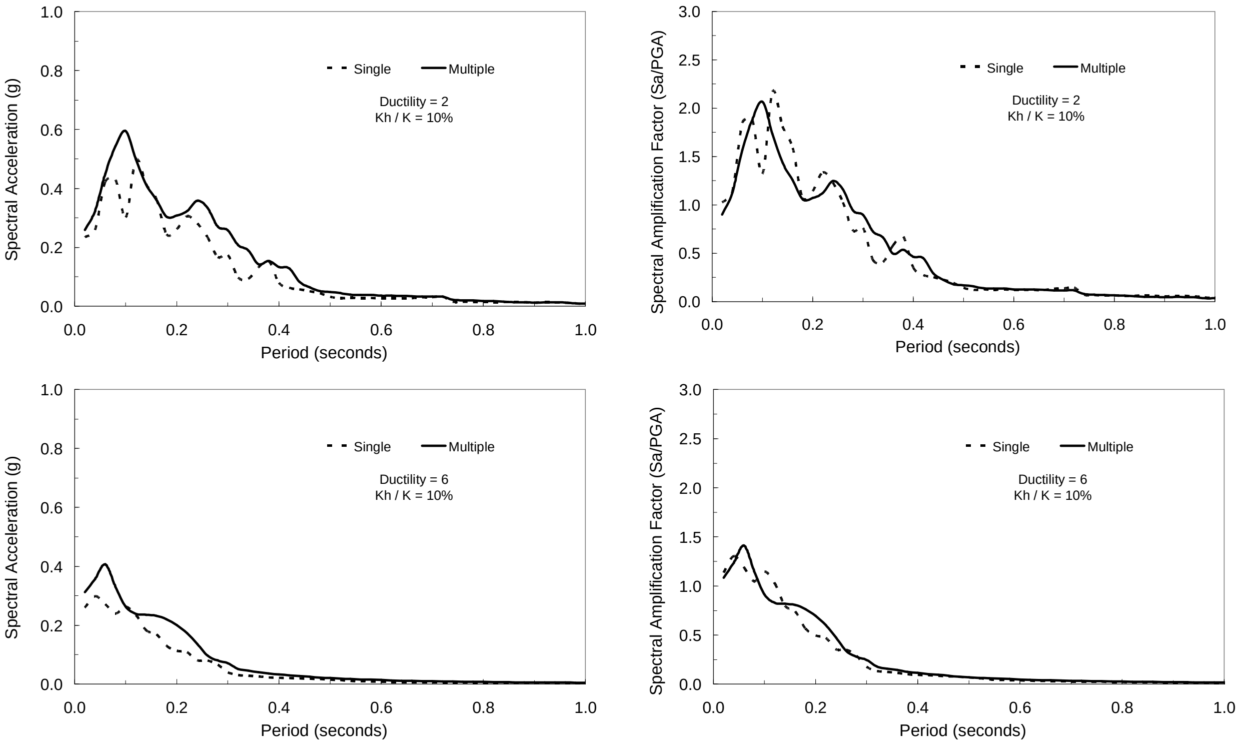

Figure 2. – Inelastic response spectra for ductility 2 (*top*) and 6 (*bottom*); Funehiki Station for the stiffness degrading hysteretic model with 10% hardening: spectral acceleration (*left*) and spectral amplification factors (*right*).

The inelastic response spectra computed for the Hitachi Station (IBR003), which includes a set of records with the second having the highest PGA, are displayed in Figure 3 for the hysteretic model with 5% hardening and ductility μ=2 and μ=6. It is found that for IBR003 the inelastic demand due to the multiple earthquakes is still higher than that of a single event. However, the variations between the spectral acceleration amplifications are higher than those computed for the Funehiki Station (FKS008). Such variations may be attributed to the significant ratio of the PGA of the first and second record in the seismic sequence, i.e. 1.91 = 0.532 / 0.278. The above ratio is 1.22 = 0.279/0.229 for the multiple records used for FKS008.

It is also observed that the spectral amplifications computed for IBR003 are higher than FKS008 counterparts. At 0.12 seconds and low ductility, the amplification for the seismic sequence of IBR003 is about 2.2; the value for the single event is about 25% lower. For FKS008 the amplifications are on average 10%.

For Hitachi Station, the presence of the second record in the sequence with the highest PGA has caused a significant period elongation as also shown in Figure 3, where the plots relative to the multiple earthquakes exhibit higher amplifications at longer periods. For periods of vibration lower than 0.20 seconds, the above elongation is about 40%. Moreover, the ductility level has a minor effect on such period elongation.

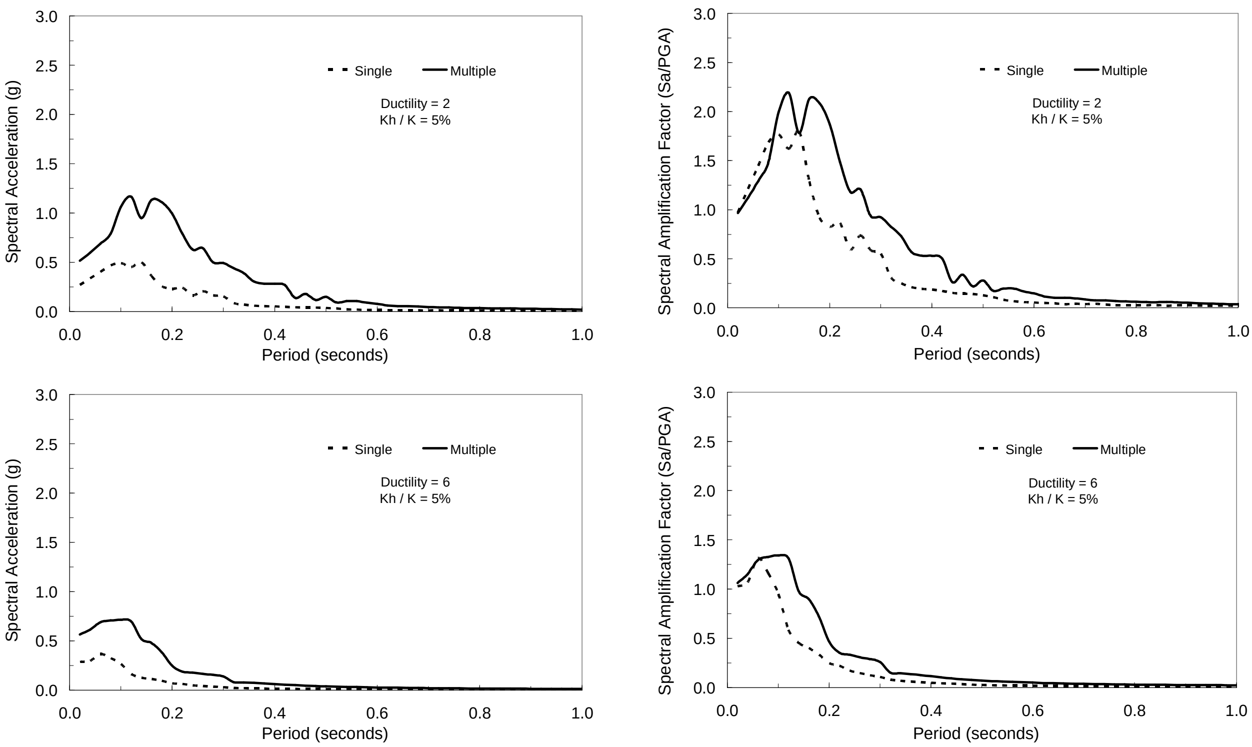

Figure 3. – Inelastic response spectra for ductility 2 (*top*) and 6 (*bottom*) and Hitachi Station for the stiffness degrading hysteretic model with 5% hardening: spectral acceleration spectra (*left*) and spectral amplification factors (*right*).

From a structural design standpoint, it is instructive to compare the normalized strength $\eta = Fy / M \cdot PGA$, where Fy is the yield force and M the mass of the SDOF, for the sample single and multiple earthquakes. Figure 4 provides the normalized strength ratios η, defined as $\eta^* = \eta_{multiple} / \eta_{single}$, for Hitachi Station, i.e. the station with the second record having the highest value of PGA in the seismic sequence. The results are for the stiffness degrading hysteretic model with 5% and 10% hardening.

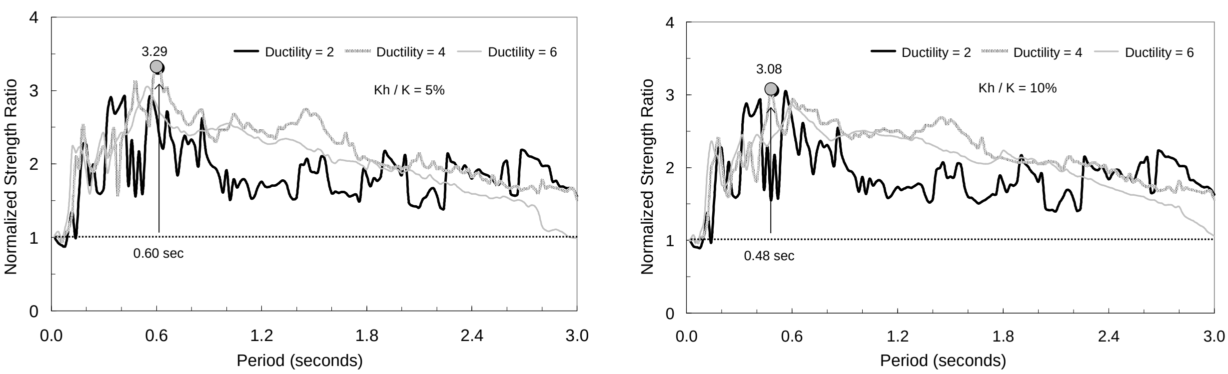

Figure 4. – Normalized strength ratio spectra for the Hitachi Station: stiffness degrading hysteretic model with 5% (*left*) and 10% (*right*) hardening.

Key: The spectra corresponding to single earthquakes are used as benchmark.

It is observed that the normalized strength for multiple seismic events can be thrice that relative to a single event and can be significantly influenced by the ductility levels, especially for periods greater than 1.0 second. The ratio η is greater than 2 for low period systems, i.e. with periods lower than 1.0 second, and tends to the unity for long period structures for high ductility levels. The maximum value of η computed for Hitachi Station is 3.29 at 0.60 seconds; it refers to ductility 4 and 5% hardening. For higher hardening, e.g. 10%, the value of η has a minor reduction (from 3.29 to 3.08, see also Figure

2); nevertheless, the maxima of η are found for shorter periods, e.g. 0.48 versus 0.60 seconds relative to 5% and 10% hardening, respectively.

3.2 Displacement Response

Comprehensive analytical studies have been carried out to estimate maximum inelastic displacement demands (Miranda and Ruiz-Garcia, 2002) and inelastic displacement ratios for the evaluation of existing structures (Ruiz-Garcia and Miranda, 2003). Such studies do not consider, however, multiple earthquake effects. More recently, steel (Ruiz-Garcia and Negrete-Manriquez, 2011) and RC (Hatzigeorgiou and Liolios, 2010) multi-storey building structures under as-recorded and/or artificial seismic main and after-shocks have been investigated. The outcomes of the analyses performed on above steel and RC structures appear, however, contradictory. On one hand, it was found that as-recorded aftershocks do not significantly increase peak and permanent drift demands of existing. It was stated that the above response is due to the frequency content of the aftershock, which is shorter, and in some cases smaller, than the frequency of the sample structures at the end of the main-shock. On the other hand, Hatzigeorgiou and Liolios (2010) studied the response of 4 regular and 4 irregular RC frames under 5 as-recorded and 40 artificial sequences and concluded that the frames consistently increased their displacement ductility demands when subjected to the 5 real seismic sequences. It is believed that the above studies focusing on the evaluation of the displacement response for multiple earthquakes have been misleading because they did not consider adequately that displacement demands depend significantly on the type of hysteretic response of the sample structures, whether degrading or not degrading, and source-to-site earthquake parameters, especially magnitude and distance. To shed light on the matter, the inelastic displacement response spectra for the strong motions recorded at the 5 sample stations during the 2011 Tohoku (Japan) earthquake were computed for different levels of ductility and type of hysteretic model for the SDOF systems. Degrading and non-degrading models were also quantify adequately the reduction of energy absorption and dissipation due to the effects of multiple earthquakes. The application of seismic sequences lead consistently to higher inelastic deformation demands than single events. The results show that the above response is not significantly affected by the system ductility and the period of vibration, especially in the range 0.5 to 2.5 seconds, which corresponds to the periods for most of new and existing structures in practical applications. Figure 5 illustrates, for example, the inelastic drift ratios, i.e. the ratio of the inelastic displacement spectra, for the Funehiki and Hitachi Stations for ductility 2(low) and 6 (high). Hysteretic stiffness degrading models with 5% and 10% hardening were considered in the analyses.

The maximum value of inelastic drift ratio is found for Hitachi Station: about 4 for a SDOF system with a period of vibration of about 2.5 seconds. The triad of ground motions recorded in Funehiki have similar values of PGAs (*see* also Table 1): they range between 0.229g (FKS008-1 record) and 0.288g (FKS008-3 record). The maximum inelastic drift ratio computed for Funehiki is 1.9 at about 0.3 seconds. The values of PGAs used for Hitachi Station range between 0.1g (IBR003-3 record) and 0.532g (IBR003-2 record), i.e. the maximum PGA in the sequence is twice that used for Funehiki. The IBR003-2 record corresponds to a M_L= 7.7 seismic event; the FKS008-3 was registered for a M_L= 6.1 earthquake. It can thus argued that the inelastic drift ratios are significantly affected also by the magnitude. The effect of the source-to-site distance should be further investigated.

3.3 Force Reduction Factors

The force reduction factor ‘demand’ represents the minimum reduction coefficient corresponding to a specific level of ductility obtained from inelastic constant ductility spectra and elastic spectra at a given period; it is computed as follows:

$$\text{Force Reduction Factor} = \frac{S_{a_{elastic}}(T)}{S_{a_{inelastic}}(T)} \qquad (1)$$

where $Sa_{elastic}$ and $Sa_{inelastic}$ are the elastic and inelastic response spectral ordinates corresponding to a specific period T, respectively. The ratio of the elastic-to-inelastic spectra changes with period, ductility factor and earthquake record. The relationship between displacement ductility and ductility-dependent behaviour factor has been extensively studied in the past decades (e.g. Newmark and Hall, 1982; Krawinkler and Nassar, 1992; Miranda and Bertero, 1994; Vidic et al., 1994; Borzi and Elnashai, 2000). However, the previous studies focused primarily on a single seismic event. More recently, Hatzigeorgious (2010-a; 2010-b) has investigated the effects of multiple earthquakes on force reduction factors; however, the study did not account for hysteretic models with stiffness and/or strength degradation.

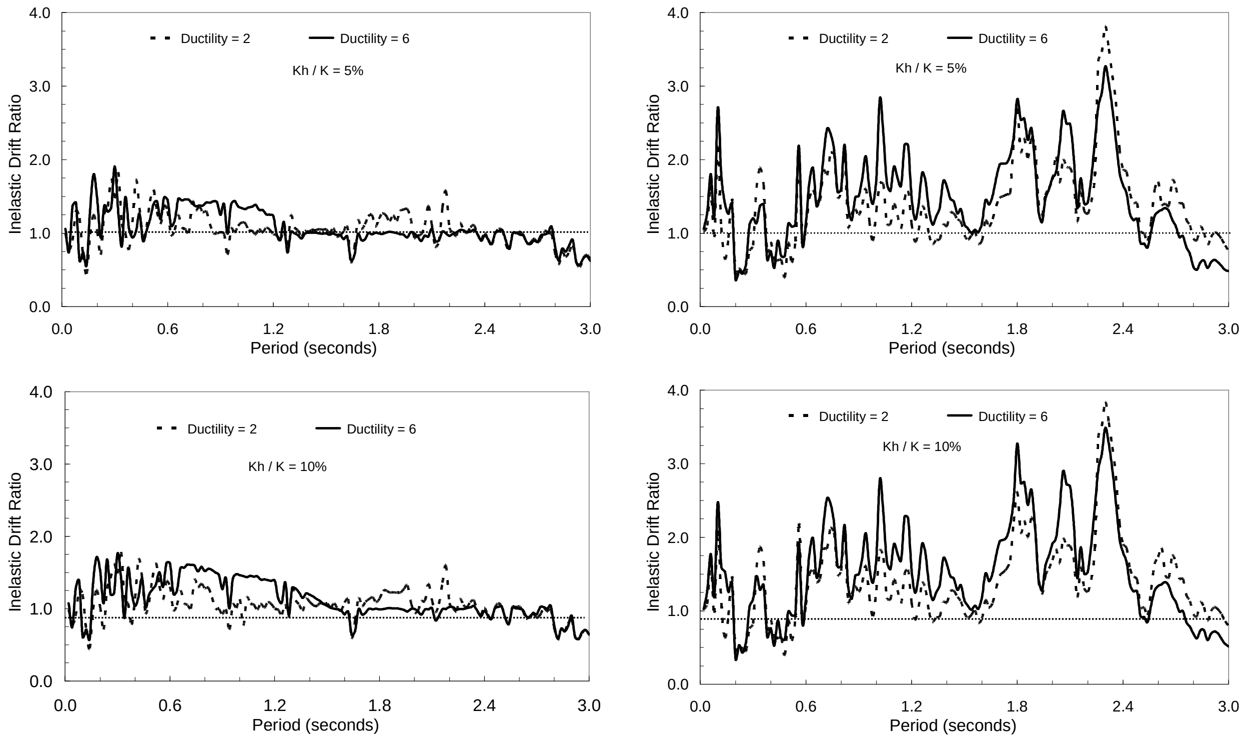

Figure 5. – Inelastic drift ratio spectra for ductility 2 and 6: Funehiki (*left*) and Hitachi (*right*) Stations for 5% (*top*) and 10% (*bottom*) hardening in the hysteretic model.

Key: The inelastic spectra corresponding to single earthquake are used as benchmark.

Elastic-plastic non-degrading SDOF systems tend to exhibit higher energy absorption and dissipation than degrading systems. Use of R-factors based on elastic-plastic response should therefore be treated with caution, especially for high levels of inelasticity.

Force reduction factors were estimated for the suite of multiple earthquake records presented in Section 2 and for different hysteretic models according to eqn.(1). Stiffness degradation models were also consider to simulate the response of RC and masonry structures as well as slender steel structures. The results show that the reduction factors for multiple events can be significantly lower than those computed for a single record. For example, underestimations of 50 to 60% were computed for Funehiki and Hitachi stations, for periods of about 0.3 seconds and about 2.0 seconds, respectively, as shown in Figure 6 for low ductility level and hysteretic model with stiffness degradation. The values of force reduction factors corresponding to the formulation by Newmark and Hall (1982) have also been included in the figure as a benchmark; their approximation is acceptable for medium-to-long period systems. However, in the short-period range, e.g. for periods lower than 0.5 seconds, the force reduction factors for single event are systematically higher than the multiple event counterparts.

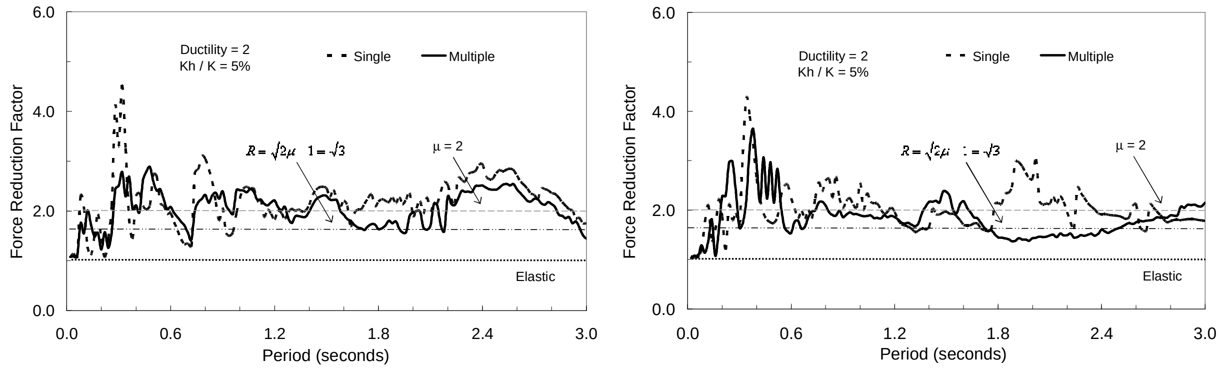

Figure 6. – Force reduction factors (ductility 2): for Funehiki (*left*) and Hitachi (*right*) Stations.

Force reduction factor ratios, i.e. the ratio of the factors relative to the seismic sequence and the single event, were also computed for further investigate the conservatism, if any, of the existing force-based methods. The results in Figure 7 show the reduction factor ratios for Funehiki and Hitachi stations, for low-to-high value of ductility.

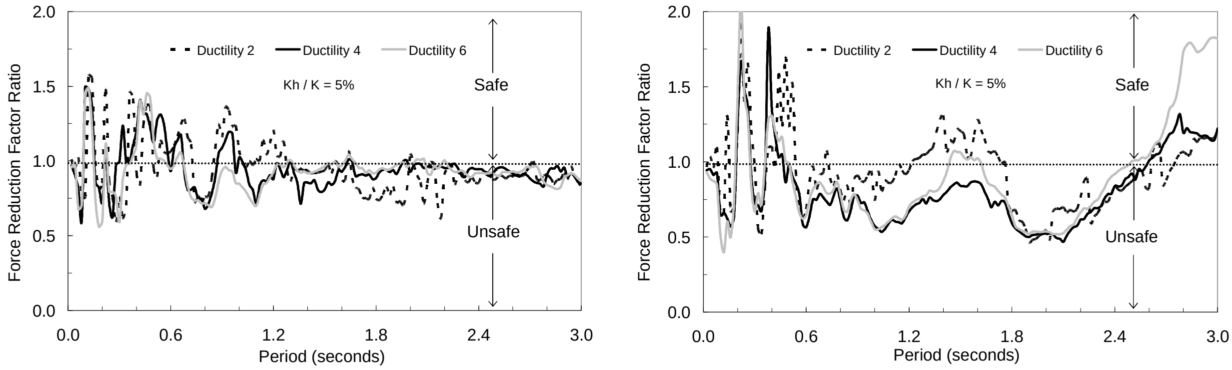

Figure 7. – Force reduction factor ratios: for Funehiki (*left*) and Hitachi (*right*) Stations.
Key: The values corresponding to single earthquake are used as benchmark.

It is noted that the effect of ductility levels depend on the earthquake and on the period of vibration. The force reduction ratios vary significantly when the ductility increases from 2 to 6 for periods ranging between 0.5 and 1.2 seconds for Funehiki and for periods between 0.4 and 1.8 seconds for Hitachi. For the multiple earthquakes with the intermediate records having the highest PGA the force reduction factor ratios are the highest (*see* also Figure 7)

4. CONCLUSIONS

This paper assesses of the effects of multiple earthquakes on structures. Inelastic constant ductility acceleration, displacement and force reduction factor spectra were derived for a set of strong motions registered at five stations during the 2011 Tohoku (Japan) earthquake and embracing different magnitudes and source-to-site distances. Comprehensive parametric spectrum analyses were carried out with degrading (stiffness and/or strength) and non-degrading hysteretic models to account reliably for the response of reinforced concrete (RC) structure when subjected to high inelastic demand as in the case of multiple large earthquakes. Normalized strength spectra for seismic sequence have shown that the force demand on structures can be thrice that relative to a single event. Such demand is, however, significantly influenced by the ductility levels, especially for periods greater than 1.0 second. Consistently higher inelastic displacements have also been computed for multiple earthquakes. The outcomes of the present study not only confirm that multiple earthquakes warrant extensive and urgent studies, but also give indications of the levels of lack of conservatism in the safety of conventionally-designed structures when subjected to multiple earthquakes alongside guidelines for the reliable hysteretic models to employ for adequate inelastic structural performance evaluation

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