

Response of Degrading Reinforced Concrete Systems Subjected to Replicate Earthquake Ground Motions

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SUMMARY:

Limited research has addressed the seismic behaviour of structures subjected to multiple earthquakes. Repeated shaking induces accumulated damage to structures that affects their level of stiffness and strength and hence their response. Given the complexity of depicting the degrading behaviour of structures using current numerical tools, previous researchers used simplified approaches to compensate for the absence of important numerical model features of stiffness and strength degradation, alongside pinching of load-displacement loops. In this paper, the aforementioned features were modelled on the material level by using a plastic energy-based degrading concrete model and a steel model that considers accumulated damage under large amplitude plastic excursions. Simplified structural models of reinforced concrete degrading systems are subjected to replicate ground motions and the response of these systems under the first (for undamaged systems) and second (for damaged systems) identical motions is compared and conclusions are drawn. It is confirmed that previous research that dismissed the effect of multiple earthquakes lacked the salient modelling features, and that including appropriate degrading constitutive relationships leads to reversing previous recommendations. The effect of multiple earthquakes on earthquake safety can be very considerable.

Keywords: Multiple earthquakes, reinforced concrete structures, damage accumulation, degrading models.

1. OVERVIEW AND PROBLEM STATEMENT

Multiple earthquakes occur in many regions around the world where complex fault systems exist. It is usually hard to define the earthquake sequence as fore-, main- and after-shocks or earthquakes from proximate fault segments. Many buildings collapse due multiple earthquakes as a result stiffness and strength deterioration in their structural materials that experience repeated earthquake loading conditions. In some cases buildings stay intact in the larger main-shocks and collapse in a small subsequent after-shock as shown in **Figure 1**.



Figure 1. Damaged building after the main-shock of Gediz earthquake in March 28, 1970 (left); the same building after a smaller after-shock (right) – After N.N. Ambraseys, private communication

Reinforced concrete structures are vulnerable to multiple earthquake excitations. Previous researchers have been focusing mainly on the seismic vulnerability of structures under the most damaging earthquake, and hence neglecting the effects of accumulated damage which is induced due to prior shaking. The damage accumulation deteriorates the stiffness and strength of structural systems in a manner that can alter their dynamic characteristics and hence their response if subjected to subsequent earthquakes. This response cannot be easily predicted from simple analysis where damage features are neglected.

The main goal of this study is to determine the effect of stiffness and strength degradation on the behaviour of reinforced concrete structures subjected to multiple earthquakes. For simplicity, replicate earthquake motions are considered in this study. Numerical models of reinforced concrete structures incorporating degrading features are established utilizing plastic energy damage concrete (Fenves 1998) and modified Menegotto-Pinto steel material models (Gomes 1997). The numerical models were subjected to two identical ground motions applied in series. The response under the first (undamaged case) and second motion (taking into account the induced damage under the first motion, damaged case), is compared and conclusions are drawn.

2. PREVIOUS RESEARCH

A literature review is conducted to establish a solid starting point to pursue the present study. Simplified SDOF systems incorporating inelastic hysteretic force-displacement relationships were studied under repeated earthquake by Mahin 1980; Aschheim et al. 1999; Amadio et al. 2003; and Hatzigeorgiou et al. 2009. MDOF frame systems were introduced by Fragiaco et al. 2003; Ellingwood et al. 2007; Hatzigeorgiou et al. 2010; and Garcia et al. 2011. In the MDOF frame systems, researchers used inelastic moment rotation relationships at beam column connection to simulate an approximate behaviour of the frames when plastic hinges at these locations are developed, this approach assumes elastic behaviour at beam and column elements. The moment rotation relationships that were used incorporated deterioration features in stiffness and strength at beam-column connections due to repeated earthquake loading.

The main conclusions drawn from previous literature are: (1) aftershocks do not have a significant impact on the maximum displacements and damage of SDOF systems, more research is advised to be conducted taking into account effect of stiffness and strength degradation of the systems under long duration earthquakes and aftershocks (Mahin 1980); and (2) prior earthquake shaking has a minor influence on peak displacement response, and the displacement response of initially damaged SDOF systems match with their counterparts after the systems experience the peak displacement during the earthquake (Aschheim 1999, see **Figure 2**).

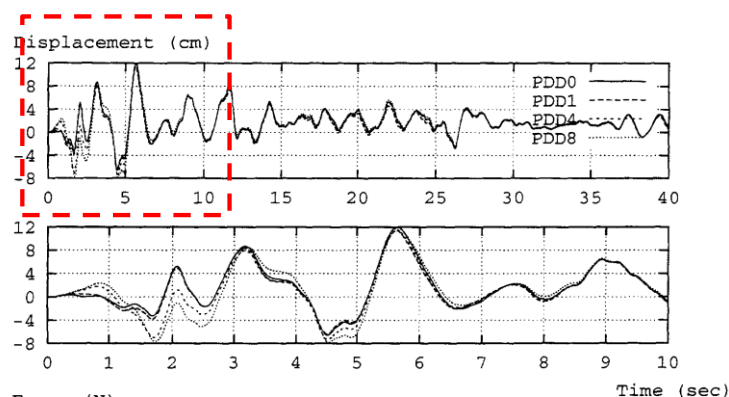


Figure 2. Displacement histories, for the total 40 (up) and first 10 seconds (down) of the response of oscillators having prior damage given by PDD = 0, 1, 4, and 8 (Aschheim, 1999)

3. MODEL DEVELOPMENT

In this study material level based models are introduced as opposed to system (SDOF systems) and component (MDOF systems assuming inelasticity at beam column connections only) level based models used in literature. The models are developed in the open source analysis tool, Zeus-NL, which is capable of performing static and dynamic analyses of structures considering material and geometric non-linearity. The current software version (v.1.9.2) contains non-degrading material models for steel and concrete in the software material library, therefore implementation of material models that account for damage accumulation is essential.

3.1. Constitutive Material Models

3.1.1. Steel model

The stress-strain relationship of steel reinforcement bars used in this study is based on the modified Menegotto-Pinto steel model (Gomes 1997). This model contains the following steel deterioration features: (1) Baushinger effect that includes reduction of yield stress and decrease of curvature between the elastic and plastic branches; (2) buckling of reinforcement bars based on equilibrium of a plastic mechanism of the buckled bar and as a function of bar diameter, stirrup spacing, and concrete crushing strain; and (3) bar fracture when the plastic strains exceed the ultimate material strain. These features are shown in **Figure 3** which represents a plot of the behaviour of a reinforcement bar under axial cyclic loading.

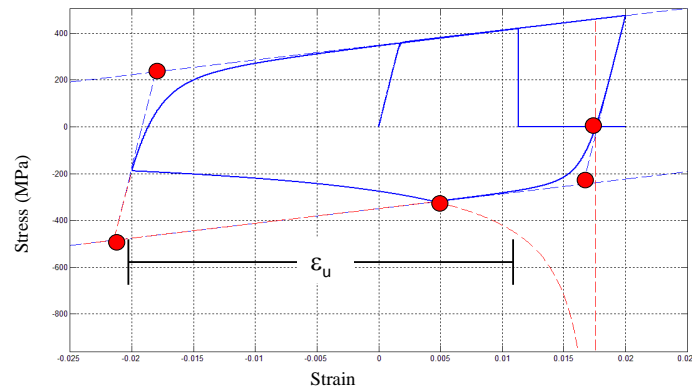


Figure 3. Baushinger, Buckling and fracture features implemented into the steel model

3.1.1. Concrete model

The concrete model is based on a plastic damage that provides an evolution of tensile and compressive stiffness and strength degradation as a function of cyclic loading conditions and level of imposed plastic strain (Fenves 1998). The model considers pinching of concrete by simulating the crack opening and closure (**Figure 4**).

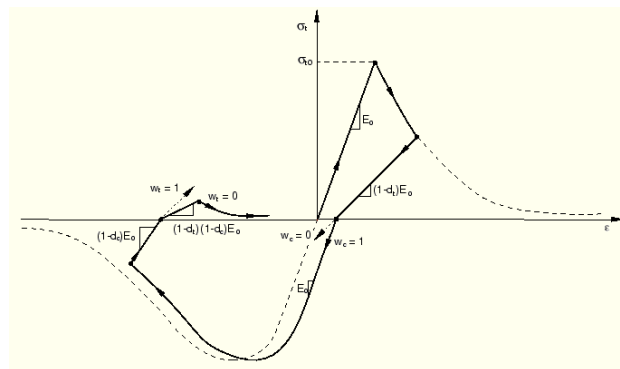


Figure 4. Stiffness and strength degradation of concrete model (Fenves 1998)

3.2. SDOF Systems

An SDOF reinforced concrete pier is studied in this section. Two modelling approaches of this system are introduced. The first approach uses the non-degrading material models for concrete (Mander et al. 1994) and steel (bi-linear stress-strain relationships), while the second approach utilizes the degrading concrete and steel models introduced in the previous section. Four SDOF systems of periods of vibration equal to 0.12, 0.22, 0.46, and 1.00 are considered in this study. Systems of different periods have the same pier cross sectional dimensions and height while the lumped mass value at the top of the pier is changed to match with the period of vibration sought. Loma Prieta acceleration record is used in the analysis. **Figure 5** shows the acceleration time histories that comprise the individual earthquake motion and the replicate one. For replicate ground motions, 10 seconds time buffer between the first and second earthquakes is assigned to allow the motion of the system to go back to rest due to damping.

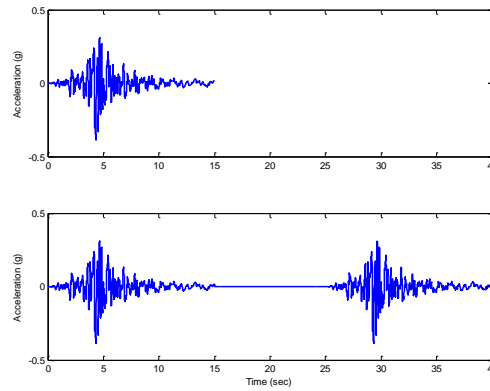


Figure 5. Earthquake ground acceleration, single (up) and repetitive (down) records

The response of the undamaged (under one earthquake only) and damaged (under the second earthquake considering prior damage induced from the first earthquake) systems is plotted in **Figure 6** using non-degrading and degrading models discussed before. The displacement response of the damaged systems using the non-degrading models matches very well with the response of their undamaged counterparts after they both reach their peak displacements. In addition, the displacement response prior to peak displacement shows period elongation in the damaged systems. This can be explained as follows: (1) the stiffness of the undamaged system at the peak displacement was reduced and kept constant throughout the whole analysis because in the non-degrading models, stiffness degradation is influenced solely by the maximum displacement the system experienced; (2) P- Δ effects play a minimal rule on stiffness degradation and that explains why the response after the peak matched very well however the response of the damaged systems experienced excessive residual displacements in some cases. On the other hand, the response of degrading systems for the damaged and undamaged cases is quite different in terms of amplitude and period of vibration before and after the system reaches its peak displacement.

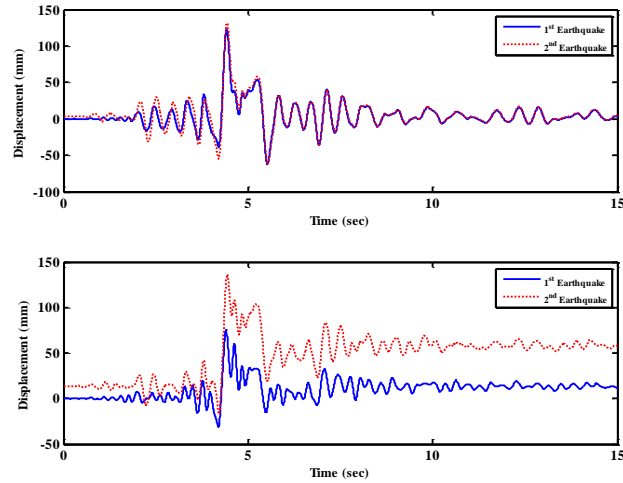


Figure 6. Response of damaged and undamaged systems using non-degrading (up) and degrading (down) models ($T = 0.22$ seconds)

The ratio of maximum displacements induced to the damaged and undamaged systems is obtained for different peak ground acceleration, PGA, scaling levels (**Figure 7**). The ratios are captured for the non-degrading and degrading cases. For the non-degrading models, displacement ratios are slightly above unity; this is due to P- Δ effects on the stiffness reduction of the non-degrading damaged models where residual displacements are introduced at the end of the first earthquake. For the degrading models, the displacement ratios are close to unity at lower PGA values where high inelasticity is not introduced to the system. Under higher values of PGA, high drift ratios, of displacement values in the damaged case reaching more than twice its undamaged counterpart, are shown. The relationship between the PGA and displacement ratio has not shown a specific trend.

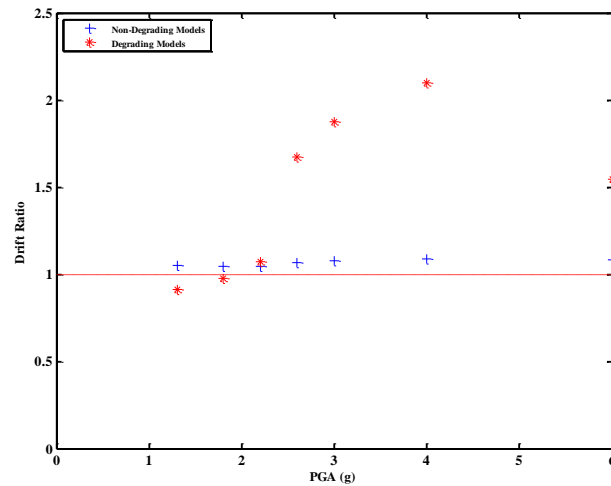


Figure 7. Effect of PGA on displacement ratio of the damaged and undamaged cases

4. CONCLUSIONS

In this study, the same earthquake is applied repeatedly to simplified inelastic systems that comprise a reinforced concrete pier with lumped mass on top. The systems utilize both non-degrading and degrading concrete and steel material models. The response of damaged and undamaged systems is discrepant in case of using models of accurate degrading features. This issue emphasizes the idea of considering multiple ground shaking effects in design and assessment of structural systems. The results presented in this study, and the conclusions drawn from them point towards the necessity of conducting detailed and comprehensive analyses of different structural systems using realistic models

to parametrically quantify the effect of multiple earthquakes on seismic response metrics. The outcome from such parameterization would then be used to formulate design procedures that result in levels of structural safety for systems subjected to more than earthquake that are consistent with current levels of safety in earthquake design codes.

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