The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

A NEW DAMAGE MODEL FOR THE SEISMIC DAMAGE ASSESSMENT OF REINFORCED CONCRETE FRAME STRUCTURES

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ABSTRACT :

In most existing reinforced concrete structures the deformation capacity deteriorates due to the low cycle fatigue effect. In order to take this effect into account in a seismic assessment, the cumulative damage caused by the energy dissipation has to be quantified. In the paper a new damage model for seismic damage assessment of reinforced concrete frame structures is proposed. It combines deformation and energy quantities at the element level in order to take into account the cumulative damage. In the new model the damage index is expressed as a deformation demand/capacity ratio. The equivalent deformation capacity is used as the available deformation capacity which takes into consideration the influence of cumulative damage. It is defined as a linear function of an energy demand/capacity ratio, and its range of values is between the monotonic and cyclic ultimate drift. In order to apply the new model, data on demands and capacities are needed. Seismic demands can be estimated by a seismic analysis of the structural model. For the estimation of capacities, some experimental data are available in existing databases on reinforced concrete elements.

KEYWORDS: Damage model, seismic damage assessment, cumulative damage, energy dissipation, reinforced concrete columns

1. INTRODUCTION

Structural damage in reinforced concrete (RC) structures during an earthquake may occur due to excessive deformations, due to accumulated damage sustained under repeated load reversals, or due to a combination of both. Several damage models used for the quantification of seismic damage include low cycle fatigue effects. An overview of damage models is presented in Chung et al. (1987), Cosenza, Manfredi (1992), Wiliams, Sexsmith (1995), Ghobarah et al. (1999), and Golafshani et al. (2005), inter alia. Cumulative damage is usually modelled either by using a low-cycle fatigue formulation, in which damage is taken as a function of the accumulated plastic deformation, or by incorporating in the damage model a term related to the dissipated hysteretic energy. The latter approach may be merely based on an energy based formulation (Akiyama, 1980), or on a combination of a deformation and an energy based formulation e.g. Park-Ang damage model (Park et al., 1984).

In the paper a new damage model for seismic damage assessment of RC frame structures is presented. It incorporates the low cycle fatigue effect where cumulative damage is quantified through energy concept. The cyclic load reversals into the inelastic range are accompanied by the energy dissipation and cause a deterioration of strength of the structural element and of the whole structure. At a given deformation the structural element is not capable of carrying the same load any more. A consequence of the energy dissipation caused by cyclic load reversals is thus a reduction of the deformation capacity of a structure. The extent of cumulative damage is related to the ratio of the dissipated hysteretic energy and the energy capacity of a structural element. The new damage index combines deformation and energy quantities. It increases with the increase of the deformation demand and with the reduction of the deformation capacity. The values of the parameters in the new model have been obtained from previous studies, which include data on demands (Fajfar, Vidic, 1994) and on capacities

(Peruš et al., 2006, Poljanšek et al., 2008) for the deformation and the energy quantities. The concept of the equivalent deformation capacity, used in this paper, is similar to the concept of the equivalent ductility (Fajfar, 1992)

2. NEW DAMAGE MODEL

The simplest measures of damage are local damage indices at the level of the element. Damage indices are defined as the demand/capacity ratio. In most cases they are dimensionless parameters that range between 0 for an undamaged structure and 1 for a structural element that attains the near collapse limit state.

It is assumed that the cyclic loading due to strong earthquake ground motion is the dominant reason for the deterioration of the deformation capacity of typical RC structures. In order to incorporate this effect in the damage model, different forms of deformation capacity are needed, i.e. the monotonic deformation capacity, the actual deformation capacity (called in this paper equivalent deformation capacity), and the cyclic deformation capacity. The monotonic and cyclic deformation capacities are usually based on empirical data obtained in experiments. In the case of cyclic loading, the loading history may influence the results. The equivalent deformation capacity is time dependent. Due to the influence of cumulative damage it decreases with increasing value of the dissipated energy. The equivalent deformation capacity is therefore lower than the deformation capacity of a structure subjected to monotonic loading. The new damage model is simply defined as the ratio between the deformation quantities

$$DI_{PF} = \frac{u}{u_{equ}} \tag{2.1}$$

where u represents the deformation demand, i.e. the maximum deformation that the structural element experiences during an earthquake, and u_{equ} is the equivalent deformation capacity of the structural element. The dependence of the equivalent deformation capacity on the dissipated hysteretic energy is defined as

$$u_{equ} = u_M - \frac{E_{H,diss}}{E_{H,cap}}\left(u_M - u_C\right) \tag{2.2}$$

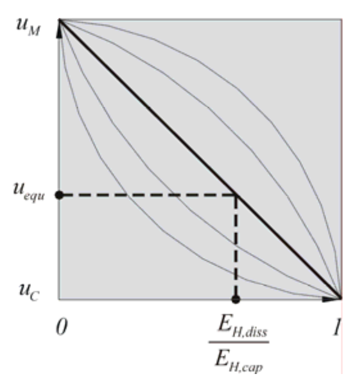

Figure 1: Linear relation between the hysteretic energy demand/capacity ratio and the equivalent deformation capacity, and possible nonlinear relations.

u_M and u_C are the deformation capacities of the structural element under monotonic loading and cyclic loading, respectively. $E_{H,diss}$ is the hysteretic energy dissipated during the ground motion, i.e. the hysteretic energy demand, and $E_{H,cap}$ is the capacity of the structural element for the dissipation of the hysteretic energy.

The maximum deformation and the dissipated hysteretic energy are estimated with seismic analyses and depend on the characteristics of the applied ground motion, whereas the deformation and energy capacities are the characteristics of the structural element. The ratio of the dissipated hysteretic energy and the hysteretic energy capacity dictates the extent of the deterioration of the monotonic deformation capacity. The equivalent deformation capacity should not fall below the cyclic deformation capacity and thus the equivalent deformation capacity has a range of values between u_M and u_C. In Eqn. 2.2 a simple assumption was introduced that the equivalent deformation capacity decreases linearly with the $E_{H,diss} / E_{H,cap}$ ratio (Figure 1). However, if needed, an option for the implementation of nonlinear relations exists.

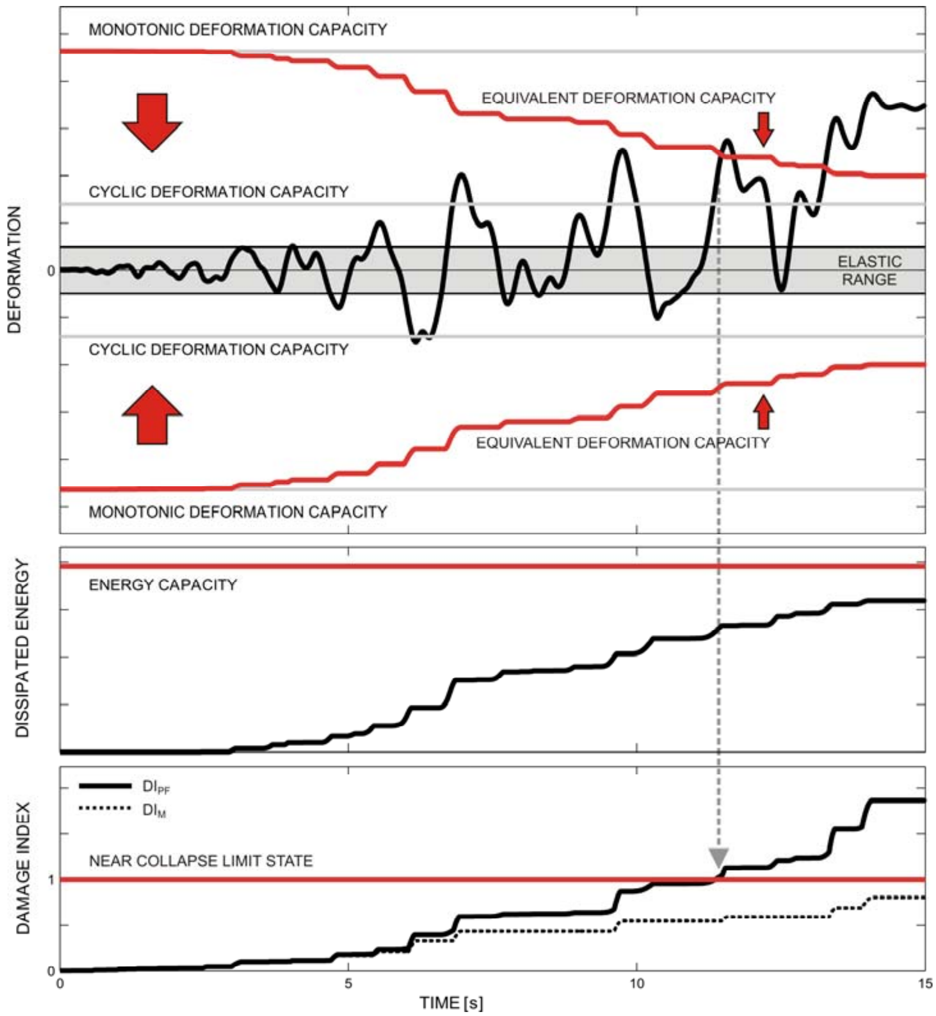

Figure 2: Time-histories of the deformation, dissipated hysteretic energy and damage indices (schematic presentation).

Considering the boundary conditions, two inconsistencies should be noted:

- In the case of the elastic behaviour of a structural element there is no hysteretic energy dissipation and the equivalent deformation capacity is equal to the monotonic deformation capacity. However, a deformation demand always exists and results in a non-zero value of the new damage index in the elastic range. This is not considered as a big disadvantage because in fact damage in RC structures occurs even before the deformation reaches the effective yield deformation.
- In the case of monotonic loading it is preferred that the damage index does not exceed the value of 1.0 when the deformation demand is equal to the monotonic deformation capacity. Because in the inelastic

range the energy is dissipated even when a structural element is subjected to monotonic loading, the equivalent deformation capacity is lower than the monotonic deformation capacity, and as a result the damage index is larger than 1.0. However, in general, the hysteretic energy dissipated under monotonic loading is small compared to the energy capacity, and a small drop in the equivalent deformation capacity may be acceptable for the sake of the simplicity of the damage model.

When the contribution of the dissipated hysteretic energy is not taken into account ($E_{H,diss} = 0$) the new damage model is of the form

$$DI_M = \frac{u}{u_M} \tag{2.3}$$

In the case of Eqn. 2.3 there is no deterioration of the equivalent deformation capacity and it is replaced by the monotonic deformation capacity which is a constant. The model defined by Eqn. 2.3 will be referred to as the monotonic damage model. It is usually used in analysis if failure is due to the maximum deformation and no consideration is given to the cumulative damage. Often it results in unsafe results. The difference in the values of the new and the monotonic damage index illustrates the influence of the cumulative damage. For illustration, the time-histories of different quantities are (schematically) shown in Figure 2, where the new damage index attains a value larger than 1.0 (indicating a near collapse limit state) due to the contribution of the cumulative damage.

3. PARAMETERS IN THE NEW MODEL

In order to apply the new model, data on demands and capacities are needed. Seismic demands can be estimated by a seismic analysis of the structural model. Seismic analyses can be performed by simplified procedures using response spectrum techniques like the N2 method (Fajfar, Gašperšič, 1996; Fajfar, 2000). For such analyses, inelastic displacement spectra (e.g. Vidic et al., 1994) and hysteretic energy spectra (e.g. Fajfar, Vidic, 1994) are needed. The estimation of the hysteretic energy demand on simple systems has been recently the aim of several studies (e.g. Manfredi, 2001; Kunnath, Chai, 2004; Iervolino et al., 2006; Arroyo, Ordaz, 2007; Ghosh, Collins 2007). If a non-linear dynamic time-history analysis is used, the seismic demand is defined by maximum values of the deformations and by the total dissipated hysteretic energy calculated at the level of the element.

In addition to demand, the capacities of the structural elements in terms of deformation (cyclic and monotonic) and energy have to be known as well. Lack of experimental databases makes it difficult to get reliable data on the capacity of structural elements as a function of the properties of the structural element. The deformation capacity of RC elements was studied by Paulay, Priestley (1992) and Fardis, Biskinis (2003) who proposed semi-empirical and empirical equations for the determination of the deformation capacities. In Eurocode 8 (2005) basically the equations by Fardis and Biskinis are used, whereas FEMA guidelines (FEMA, 2000) provide tabulated values for ultimate deformation capacities. An empirical equation for the monotonic deformation capacity is given in the IDARC manual (Park et al., 1987), whereas an empirical formula related to the hysteretic dissipation capacity was proposed by Haselton (2006). It is intended for the use in the hysteretic model by Ibarra et al. (2005).

In studies performed at the University of Ljubljana, a multidimensional nonparametric regression (the CAE - Conditional Average Estimator – method, Peruš et al., 2006) which enables the prediction of unknown quantities without prior knowledge of phenomena, was used for the determination of capacities of RC columns. Especially in the case of energy capacity, for which the prior knowledge is limited, the nonparametric approach proved to be very convenient. The CAE method requires an appropriate database of experiments or measurements where the phenomena, in our case the capacities of RC columns, are described with input parameters that represent the known characteristics of the structural element. As a result, the unknown quantities can be presented as a function of known input parameters, but only in a graphical form. For each prediction the analysis of the entire database has to be performed. Using the PEER database (University of Washington, 2005) of experiments on RC rectangular columns with flexural failure mode, some results for the deformation (Peruš et al., 2006; Peruš, Fajfar, 2007) and energy capacity (Poljanšek et al., 2008) for RC columns were obtained. Data on capacity in terms of ultimate displacement of monotonically and cyclically loaded RC elements are provided also in the Fardis database (Fardis, Biskinis, 2003). In (Poljanšek et al., 2008) they were used for the comparison between cyclic and monotonic deformation capacity.

In the studies performed at the University of Ljubljana. the capacities were estimated as a function of the following five input parameters:

- ***the axial load index*** ($P^* = P / A_c f_c^{'}$) where P is the axial force and $A_c = bh$ is the cross section of the columns (b - the width of the compression zone, h - the depth in the direction of loading),
- ***the confinement effectiveness factor multiplied by the confinement index*** ($\alpha\rho_s^* = \alpha\rho_s(f_{ys} / f_c^{'})$) where $\rho_s = A_{sx} / bs_h$ is the ratio of the transverse steel A_{sx} parallel to the direction of loading and the area of the confined concrete (s_h - the spacing of stirrups, f_{ys} - the yield strength of transverse reinforcement and α - the confinement effectiveness factor according to the definition in Eurocode 8, part 3 (2005)),
- ***the shear span index*** ($L^* = L / h$) where L represents the length of the equivalent cantilever (shear span) defined as the moment to shear ratio at the critical section,
- ***the compressive strength*** ($f_c^{'}$),
- ***the longitudinal reinforcement index*** ($\rho_l^* = \rho_l(f_{yl} / f_c^{'})$), where ρ_l is the longitudinal reinforcement ratio and f_{yl} is the yield strength of the longitudinal reinforcement.

The deformation capacity is defined as the ultimate displacement or rotation that corresponds to the 20% strength drop measured at the envelope of hysteretic loops (average of the positive and the negative branch). This is a conventional definition of a near collapse limit state. The hysteretic energy capacity is defined as the total area under all hysteretic loops that a structural element undergoes during cyclically changing lateral load, to the last point of the force - displacement history where the force is still above 80% of the maximum strength.

The output parameters, to be determined in the CAE analysis, are normalized non-dimensional parameters defining capacities: the monotonic ultimate drift δ_M, the cyclic ultimate drift δ_C, the normalized energy capacity $\bar{E}_{H,L,cap}$, and the drift ratio δ_C / δ_M. In Figure 3 the capacity parameters, δ_M, δ_C and $\bar{E}_{H,L,cap}$, are shown in percents, i.e., the computed value is multiplied by 100. The drift is equal to the chord rotation, whereas $\bar{E}_{H,L,cap}$ is related to the cumulative plastic drift. Ultimate drifts are obtained as the ratio between the displacement at the top of the equivalent cantilever and the length of this cantilever, also called shear span, whereas the hysteretic energy capacity is normalized with the strength F_y and shear span L

$$\bar{E}_{H,L,cap} = \frac{E_{H,cap}}{F_y L} \tag{3.1}$$

The results for the cyclic ultimate drift are presented in more details in (Peruš et al., 2006). Predicted values are in the range from about 3% to 6% with the average value of the experimental results in the database about 4.2%. Results for the other three output parameters are presented in more details in (Poljanšek et al., 2008). The monotonic ultimate drift decreases with an increasing axial load index and with an increasing longitudinal reinforcement index, whereas it increases with an increasing shear span index. The influence of the other two input parameters is less clear, also because there are not enough representatives in the database. The strongest influences on the drift ratio δ_C / δ_M exhibit the axial load index and the confinement. The ratio increases with an increasing axial load index, with an increasing index related to confinement, and with an increasing longitudinal reinforcement index. A slight decreasing trend is observed in the case of the shear span index. Predicted values are in the range from about 0.3 to 0.75. The average value of the drift ratio is 0.5. Energy dissipation capacity decreases with an increasing axial load index and with concrete compressive strength, and increases with better confinement and with an increasing longitudinal reinforcement index. The energy capacity increases up to a shear span index value of about 3, and decreases for larger values of the shear span index. The strongest influence exhibits the longitudinal reinforcement index. When it exceeds the value of 0.3, a synergetic effect of longitudinal reinforcement and confinement starts to increase the energy capacity rapidly. If the longitudinal reinforcement index is below 0.3, the influence of other three parameters, especially of the axial load index, becomes more visible. Predicted values of $\overline{E}_{H,L,cap}$ are in the range from about 15% to 80% with the average value of the experimental results in the database of about 30%.

Note that, in general, the energy dissipation capacity depends on the load history. The above data are based on tests subjected to a standard cyclic test procedure. Consequently, the values are limited to ground motions producing a response similar to that in a standard cyclic testing procedure, i.e. ground motions with gradually increasing amplitudes.

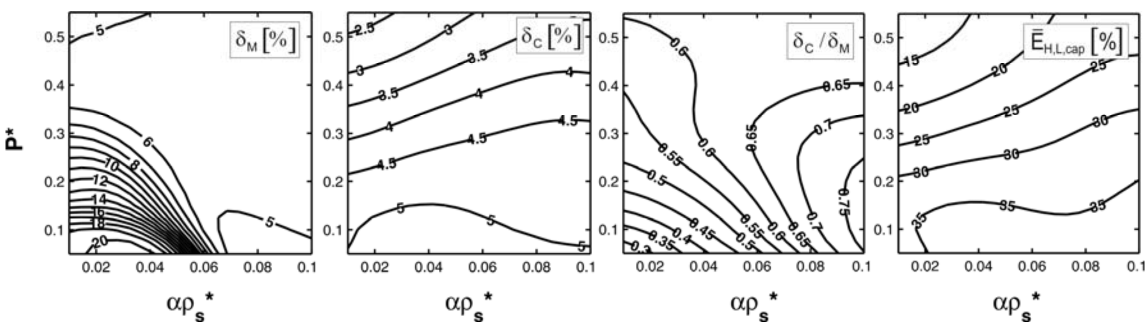

Figure 3: Normalized capacities determined for $L^* = 4$, $f_c^{'} = 30MPa$, $\rho_l^* = 0.25$.

4. COMPARISON WITH THE PARK-ANG DAMAGE MODEL

The new model has some similarity with the well known Park-Ang damage model (Park et al., 1984) which also includes the energy term

$$DI_{PA} = \frac{u}{u_M} + \beta \frac{E_{H,diss}}{F_y u_M} \tag{4.1}$$

F_y is the yield strength and β is a constant which depends in the structural characteristics and controls the strength degradation in correlation with the dissipated energy. Other parameters have the same meaning as in the proposed model. Note that the term $F_y u_M$ represents the monotonic hysteretic energy capacity.

The new damage model has some potential advantages in comparison to the Park-Ang's model, while retaining its main benefits, which is the simplicity and use of the hysteretic energy instead of the number of cycles. The proposed damage model

- incorporates a realistic hysteretic energy capacity and allows a control of its consumption by checking the ratio $E_{H,diss} / E_{H,cap}$,
- avoids the parameter β which is difficult to be estimated.

Another difference in comparison to the Park-Ang model is a nonlinear combination of the damage caused by large deformation and the one caused by energy dissipation (see Eqns. 2.1 and 2.2).

As far as boundary conditions are concerned, the new model includes similar inconsistencies as the Park-Ang model. They are described in Chapter 2.

5. CONCLUSIONS

In the paper a new damage model has been proposed that takes into account the low cycle fatigue effect using the energy concept. Due the cyclic loading caused by strong ground motion the deformation capacity of typical RC structures deteriorates. The new damage index is expressed as a ratio of the deformation demand and the equivalent deformation capacity, i.e. the actual deformation capacity which takes into account low cycle fatigue effect. The equivalent deformation capacity depends on the hysteretic energy demand/ capacity ratio, the monotonic, and the cyclic deformation capacity. Some empirical results for these quantities have been recently obtained within the research group at the University of Ljubljana. The new damage model has some similarity with the Park-Ang damage model. Compared to the Park-Ang model, the new model directly applies a realistic hysteretic energy capacity and replaces the parameter β used in the Park-Ang model with the equivalent deformation capacity.

ACKNOWLEDGEMENTS

The paper presents a part of the PhD dissertation of the first author. The work has been performed at the University of Ljubljana, Slovenia, and was funded by the Slovenian Research Agency.

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