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DRIFT BASED DAMAGE FUNCTIONS FOR COMPONENTS OF RC STRUCTURES

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SUMMARY

There are numerous reinforced concrete structures throughout the world which are highly vulnerable to seismic action. Identifying these structures is of critical importance for both reliable loss estimation after a major earthquake and setting priority criterion for strengthening of structures. Evaluating the performance of a whole structure is not easy due to lack of proper experimental and empirical data. For this reason the trend has moved to evaluating reinforced concrete structures in terms of its components.

For reinforced concrete structures, columns and beams are amongst the most important components as far as seismic performance is concerned. Moreover, as a result of the intensive research conducted it was observed that the brick infills have significant effect on the seismic behavior of structures.

With the objective of obtaining building damage functions, research has been undertaken to develop drift based damage functions for reinforced concrete columns, beams and brick infills. A broad range of parameters affecting the damageability of these components were investigated and those that were found significant were used in the damage curves proposed in terms of interstory drifts.

Once component level investigations are completed, story and then building level damage functions are developed. For a given story drift obtained from nonlinear analysis, component damage functions are combined using weighting coefficients that reflect the importance of each component. The component importance factors depend on the role of the member in resisting seismic forces.

INTRODUCTION

In the seismic behavior of reinforced concrete moment resisting frames, the behavior of the beams, columns and brick infill walls is of critical importance. If the damage level of these components as a result of a probable earthquake can be predicted with certain accuracy, then the damage level of the entire frame can also be evaluated precisely. The main motivation under evaluating the reinforced concrete frames in terms of its components rather than as a whole is that; the behavior of the components has been

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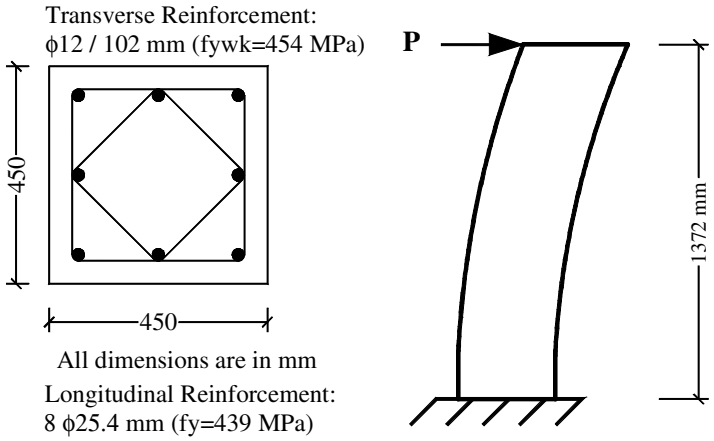
investigated in detail and is well understood than the behavior of the frame as a whole. In general, the damage level of these components is represented by a damage index which is expressed in terms of certain parameters such as ductility index, chord rotation, drift ratio, etc. In this framework, numerical studies were carried out to develop damage functions for the columns, beams and brick infills of reinforced concrete frame structures. In this study, the damage index is expressed in terms of the interstory drift ratio. In developing these functions, the effect the parameters that influence the damageability of these components were investigated numerically

Once the damage scores for all the components of a frame is determined, the next step is combining these damage scores to obtain a single damage score for the whole frame. The damage scores of the components are combined using weighing coefficients for each component. These weighing coefficients reflect the relative importance of the components within a frame and named as component importance factors. A methodology to determine the component importance factors was developed. In this methodology, the contribution of each component to the energy dissipation capacity was used as the criterion to determine the relative importance of that component.

DAMAGE FUNCTIONS FOR RC COLUMNS

Columns are amongst the most important components of RC frame structures as far as seismic behavior is concerned. Thus, predicting damage level of columns of a structure is of great importance in predicting the damage level of the structure as a whole.

To develop the damage curves for columns, several finite element analyses were carried out using the software ANSYS v6.1. Reinforced concrete was modeled using eight node brick elements that are capable of taking the cracking and crushing of concrete into account. The longitudinal reinforcement was modeled as smeared throughout the section .To take the confinement into account Modified Kent and Park model [1] was used. In the analyses carried out, it was assumed that the detailing of the longitudinal reinforcement was properly done so that no bond and lapped splice problems occur. The columns were analyzed under a point load applied at the tip of the cantilever as shown in Figure 1-b. Firstly, the finite element model used was validated by analyzing a column tested previously by Azizinamini et. al. [2]. This column was named as the reference column and its properties are given in Figure 1-a.



(a) (b) - Schematic

Figure 1 – Properties of the reference column and finite element model used for the columns

Further analyses were carried out to investigate the effect of certain parameters on the damageability of RC columns. The parameters investigated within the scope of this study are concrete strength (f_{ck}), amount and yield strength of longitudinal reinforcement (ρ and f_{yk}), amount of transverse reinforcement (ρ_s), axial load level (N/N_o; N being the axial load on the column and N_o is the nominal axial load capacity) and the slenderness ratio (L/i; L is the length of the column and i is the radius of gyration).

The damage criterion used in the development of the damage curves for RC columns was mainly based on two points of the capacity curves (lateral load vs. top displacement) of the columns. These two points are the yield drift ratio and the ultimate drift ratio. In this study, four levels of damage were identified: Negligible, light, moderate and heavy damage. For the determination of the first three damage levels, crack widths were used. In the computation of the crack widths, the formula proposed by Frosch [3] was used. The negligible damage state covers the 0% to 1% damage. A crack width of 0.2 mm was considered to be at the midrange of the negligible damage state and was assigned a score of 0.5%. The light damage state covers the damage score range of 5% to 10%. A crack width of 1 mm was considered to be an indicator of light damage and was assigned a damage score 7.5%. For the moderate damage state, which covers the 10% to 50% damage score range, the crack width of 2 mm was used and this width was assigned a damage score of 30%. As a result of a series of pushover analyses on columns with low axial load level, it was observed that these crack widths occur at ductility indices of 0.2, 0.6 and 1.0, respectively. In the light of this discussion, the ductility indices of 0.2, 0.6 and 1.0 were assigned to the damage scores of 0.5%, 7.5% and 30% respectively. A damage score higher than 50% corresponds to heavy damage. For the heavy damage state ultimate ductility index was used instead of crack widths. For this, the ultimate ductility index for each column was computed and was assigned a damage score of 90%.

Of the parameters investigated, the yield strength of the longitudinal reinforcement and the slenderness ratio affect the yield drift ratio significantly. Since the damage criterion used herein depends on this term, these two parameters affect the damage curves. Their effects on the damage curves were reflected through correction factors (C_{fy} and C_s). As a result of the analyses carried out, it was observed that concrete strength and amount of longitudinal reinforcement does not have significant affect on the damageability of RC columns provided that all the other parameters are kept constant. The amount of transverse reinforcement and axial load level affect the ultimate ductility of RC columns significantly. The effects of these parameters on the capacity curves of RC columns were observed to be very similar to each other. An increase (decrease) in the amount of transverse reinforcement affects the capacity curves of the columns just in the way a decrease (increase) in the axial load level does. Considering this fact, a new term defined as the ratio of the amount of transverse reinforcement to the axial load level ($\rho_s/(N/N_o)$) was introduced. Then, the columns analyzed were grouped into three based on their ($\rho_s/(N/N_o)$) values. The columns with a ($\rho_s/(N/N_o)$) value less than 0.05 were considered to be of low ductility. If the ($\rho_s/(N/N_o)$) value of a column is between 0.05 and 0.10, then the ductility of this column was considered to be moderate. The ductility level of a column is considered to be high if its ($\rho_s/(N/N_o)$) value exceeds 0.10.

After the parametric study had been completed, the damage curves for three ductility levels were developed. First, the columns analyzed were grouped into three according to their ($\rho_s/(N/N_o)$) values. Then, the drift ratios corresponding to the four damage levels were obtained for each column based on the ductility indices that had been determined. When the database formed reached to sufficient size, the damage curves were fit using the least squares curve fitting technique. Here it must be noted that the yield strengths and the slenderness ratios of the columns in the database that was used in the curve fitting was constant. As indicated before, the effect of these parameters were taken into account via the introduction of correction factors. The form of the damage function developed is given in Equation 1.

$$Damage(\delta) = \left(1 - e^{\left(\frac{\delta}{a(C_s)(C_{fy})}\right)^b}\right) g(\delta) \tag{1}$$

where g(δ) is given in Equation 2:

$$g(\delta) = 0.5\left[1 - \cos\left(\frac{\pi\delta}{c(C_{fy})(C_s)}\right)\right] \qquad \text{if } \frac{\delta}{C_s C_{fy}} \le c$$

$$g(\delta) = 1 \qquad \text{if } \frac{\delta}{C_s C_{fy}} > c \tag{2}$$

In Equations 1 and 2, δ is the drift ratio, C_s and C_{fy} are the correction factors for slenderness ratio and yield strength of longitudinal reinforcement, respectively (Eqs. 3 and 4), a, b, and c are the equation parameters.

$$C_s = 0.045\left(\frac{L}{i}\right) \tag{3}$$

$$C_{fy} = 0.4\left(\frac{f_y}{439}\right) + 0.6 \tag{4}$$

The equation parameters a, b, and c were detemined for each ductility level using the least squares curve fitting technique.

Figure 2 presents the mean damage functions for all ductility levels. Detailed information about the development of drift based damage functions for reinforced concrete columns is given elsewhere [4].

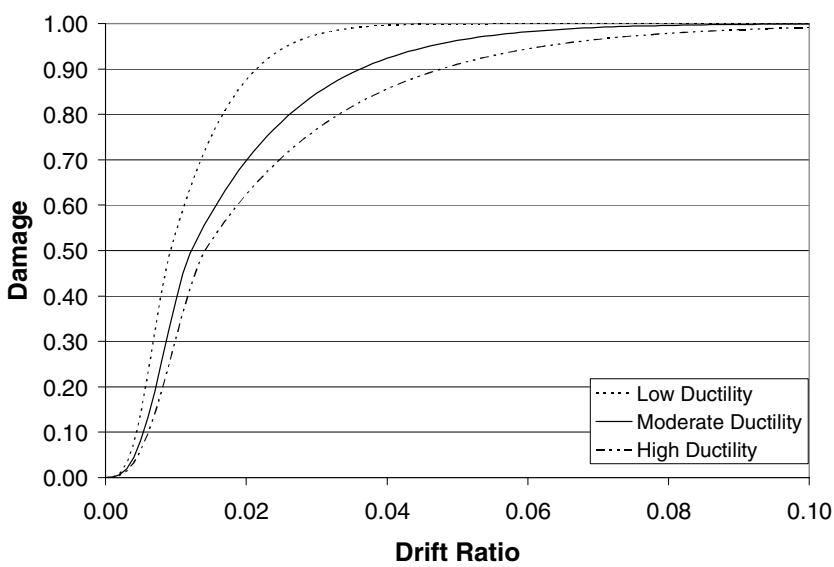


Figure 2 – Mean Damage curves for columns

The damage functions developed for reinforced concrete columns were compared with observed damage cases for validation. For this, 42 columns, whose cyclic load deformation curves were available form test

data were used. The properties and test results of these columns were obtained from NISTIR report [5]. The comparison was made at two critical points, namely the yield drift ratio and ultimate drift ratio. In addition, the observed damage cases were compared with the methodologies proposed by Telemachos & Fardis [6] and Priestly [7] (Table 1, Figures 3 and 4).

Table 1 - Comparison of the developed damage functions with experimental data

	This Study		Telemachos & Fardis (with slip)		Telemachos & Fardis (without slip)		Priestly	
	Mean	COV	Mean	COV	Mean	COV	Mean	COV
$\delta_{y\text{-pred}}/\delta_{y\text{-obs}}$	0.94	0.22	1.17	0.18	0.90	0.19	0.79	0.21
$\delta_{u\text{-pred}}/\delta_{u\text{-obs}}$	1.02	0.27	1.86	0.27	1.24	0.27	1.61	0.28

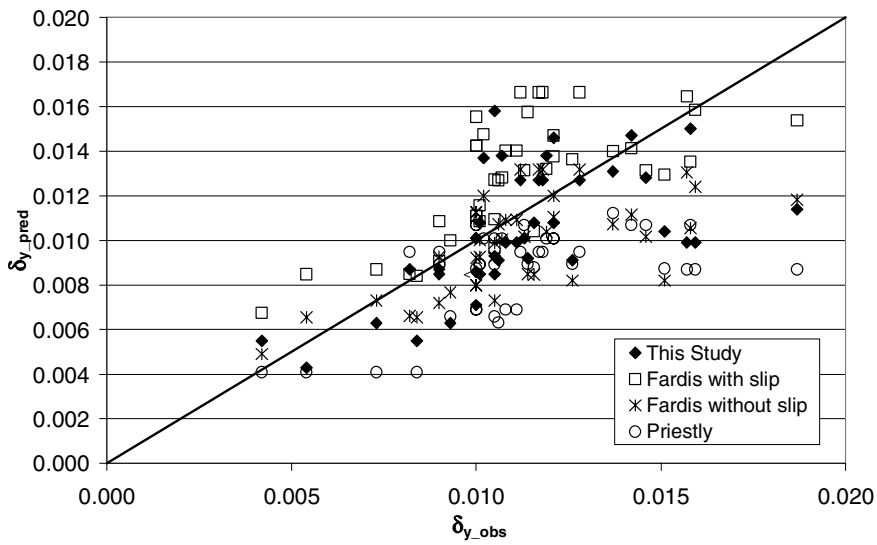


Figure 3 – Predicted and observed values for yield drift ratio of RC columns

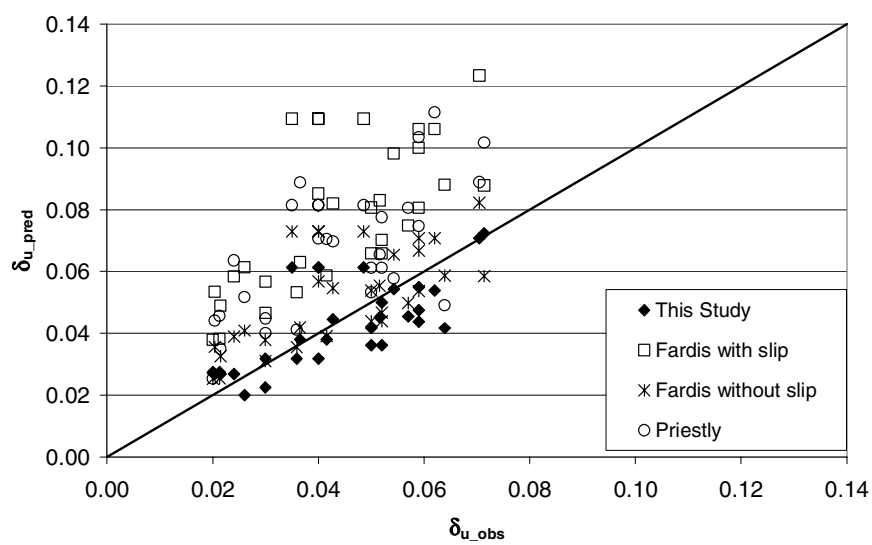


Figure 4 - Predicted and observed values for ultimate drift ratio of RC columns

DAMAGE FUNCTIONS FOR RC BEAMS

Damage in the beams can directly be related to the rotations at the ends rather than the interstory drift ratio. The response of the beams to the lateral deformations may vary significantly by the variations in the structural system. Thus, it was thought that it would be more appropriate to express the damage functions for the reinforced concrete beams in terms of the rotations at the member ends rather than the interstory drift ratio. Then, a detailed study was carried out to investigate the drift – rotation relationships and the beam end rotations were expressed in terms of the interstory drift ratio. By this way, it was possible to express the damage in the beams in terms of interstory drift ratio.

To develop the damage functions for RC beams, a portal frame was modeled in ANSYS v6.1. The columns of this portal frame were assumed to remain elastic during all stages of the loading. The frame was loaded through the application of lateral displacements to the upper nodes of the columns. Reinforced concrete was modeled in the same way as in the case of RC columns. To monitor the damage level of the beams, crack widths at a section which is d/2 units away from the face of the column (d being the depth of the beam) were used. The expression proposed by Frosch [3] was used to compute the crack widths. In this study rotation was defined as the chord rotation measured between two sections, one of which is just at the face of the column and the other is d/2 units away from the column face (i.e. the section at which the crack width was monitored). Figure 5 shows the definition of the chord rotation used in this study. As in the case of columns, crack widths were used to determine none to moderate levels of damage. For heavy damage case, moment curvature and in turn moment rotation relations were used.

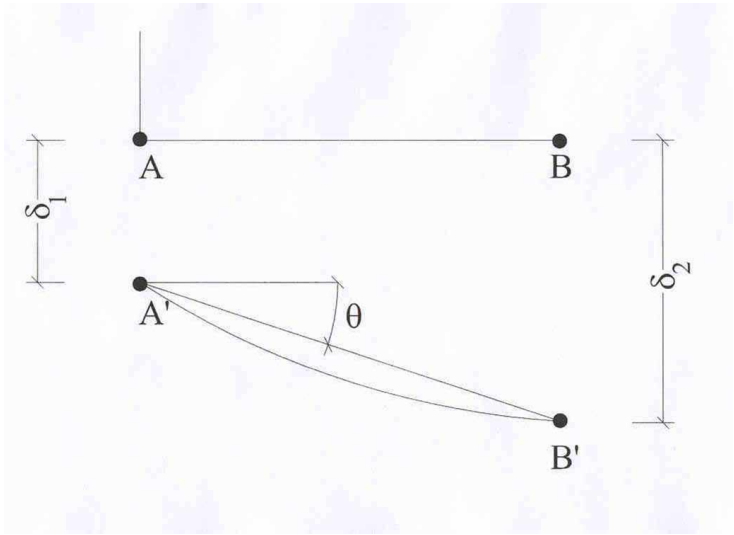


Figure 5 –The definition of chord rotation

As the first step, the effect of several parameters on the damageability of RC beams was investigated. These parameters are the concrete strength (f_{ck}), yield strength of longitudinal reinforcement (f_{yk}), amount of tension and compression reinforcement (ρ and ρ'/ρ) and depth of the beam (d). When the crack width – rotation curves were examined, it was observed that the most significant parameters affecting the damageability of RC beams in the none to moderate levels of damage are the depth of the beam and yield strength of the beam. Moreover, it was observed that the amount of tension and compression reinforcement has no significant effect on the rotation - crack width curves, whereas concrete strength affects these curves to some extent. As stated before, for the heavy damage case, the moment – rotation relationships were used. The effect of the aforementioned parameters was investigated based on their influence on the yield rotation and ultimate rotation ductility. Of the parameters investigated, all but depth

of the beam affect the ultimate rotation ductility of the beams significantly. Depth of the beam affects the yield rotation significantly. Recalling that the depth of the beam affects the damageability of the beams in none to moderate levels of damage, it was concluded that this term affects the behavior of the beams at all stages and it was decided to take its effect into account by means of a correction factor (C_d). To take the effect of the remaining parameters into account, the beams analyzed were grouped into three. It was observed that the ultimate rotation ductility of the beams increases with increase in concrete strength and amount of compression reinforcement and decrease in the amount of tension reinforcement and yield strength of longitudinal reinforcement. Based on this discussion, the criterion used for grouping beams was selected as the ratio of product of (ρ'/ρ) and f_{ck} to the product of ρ and f_{yk} $[(\rho'/\rho).f_{ck}]/(f_{yk}.\rho)$. If the $[(\rho'/\rho).f_{ck}]/(f_{yk}.\rho)$ value of a beam is less than 2, then this beam is considered to be of low ductility. If this value is between 2 and 3 for a beam, then the ductility level of that beam is moderate. The ductility level of a beam is considered to be high if its $[(\rho'/\rho).f_{ck}]/(f_{yk}.\rho)$ value exceeds 3.

For negligible, light and moderate levels of damage, the damage criterion used for the columns was also adopted for beams. The rotation at which the plastic rotation of the beam is 75% of its ultimate plastic rotation capacity was chosen as an indicator of heavy damage and was assigned a damage score of 0.75. Then, the rotation – damage score points were plotted for each group and damage functions similar to the ones developed for the columns (Eqs 1, 2) were formed and presented in Figure 6.

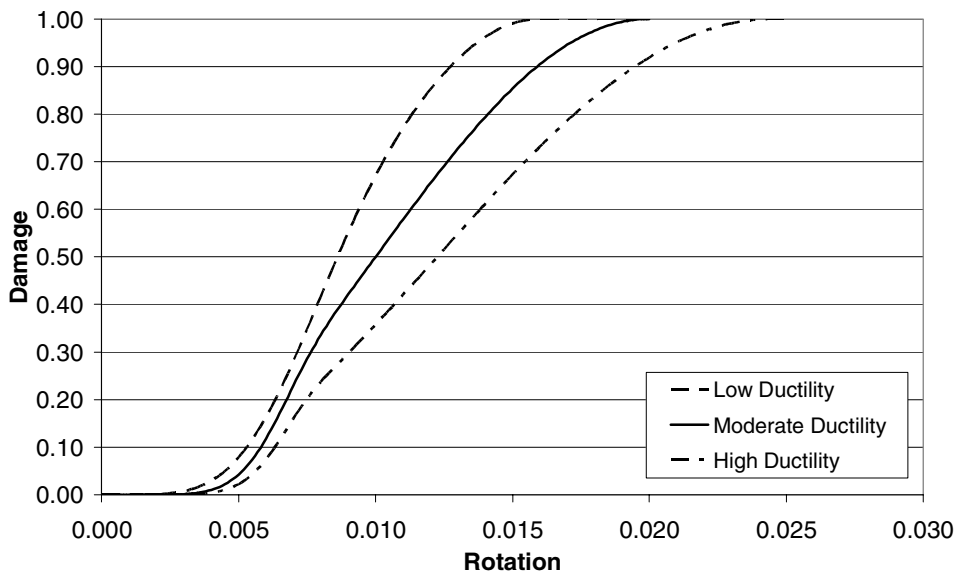


Figure 6 – Mean Damage Curves for RC Beams

After the development of the rotation based damage functions for the beams, studies were carried out to express the rotation in terms of the interstory drift ratio which would enable the expression of the damage in terms of the drift ratio. For this purpose several pushover analyses were carried out. In these analyses the effect of several parameters on the drift ratio – rotation relationship were investigated. These parameters were the concrete strength, yield strength of longitudinal reinforcement, bay width, story height and beam to column capacity ratio (BCCR). At the end of the analyses carried out, it was observed that the only parameter that affects the drift ratio - rotation curves is the beam column capacity ratio. In this study, BCCR was defined as the ratio of the moment capacities of all the beams spanning into a joint to moment capacities of all the columns spanning into the same joint. In the calculation of the moment capacities of the columns, the axial load on the columns was taken as the one imposed by the gravity loading only. At the end of the analyses, mainly three drift ratio – rotation curves were observed for different BCCR values. For a BCCR value less than 0.75, the drift ratio - rotation curve is linear. If the

BCCR value is between 0.75 and 1.00, a typical drift ratio – rotation curve is bilinear. If the BCCR value exceeds 1.00, than the drift ratio – rotation relationship is again bilinear, but this time the slope of the second portion is 0. The mean drift ratio – rotation curves for the three groups are shown in Figure 7. Figure 8 presents the data points of the drift ratio – rotation relationship for the first group (i. e. BCCR≤0.75) together with the fitted line.

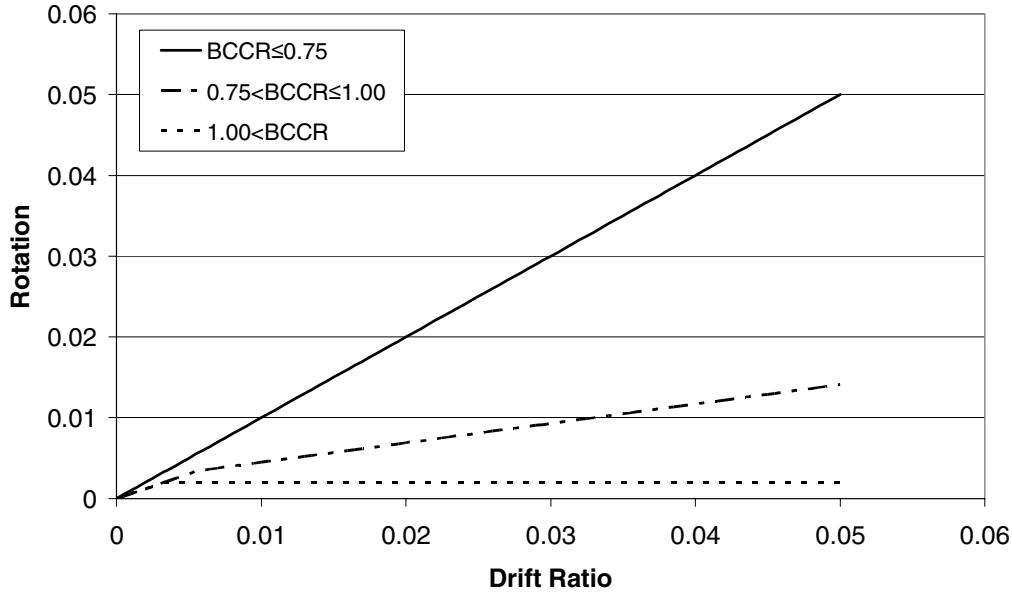


Figure 7 – Drift Ratio – Rotation Relationships

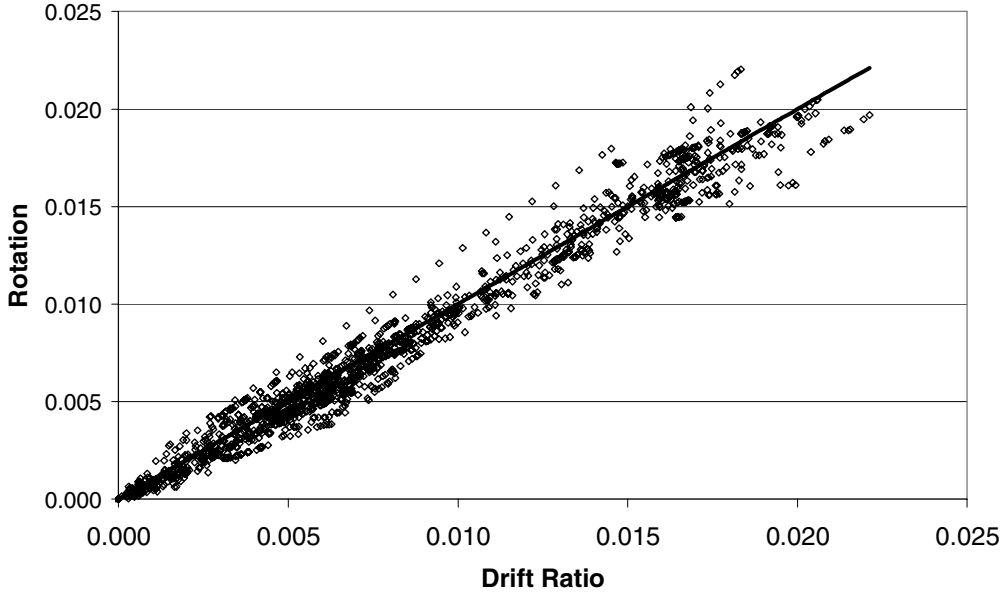


Figure 8 – Drift Ratio – Rotation Relationship for BCCR≤0.75

DAMAGE FUNCTIONS FOR BRICK INFILLS

Although they are mostly treated as non-structural elements and their contribution is neglected during the design process, it is well known that the brick infills contribute significantly to the seismic performance of reinforced concrete structures. Thus, the damageability of the brick infills must also be taken into account for a reliable vulnerability assessment. For this purpose, drift based damage functions for brick infills were developed. To develop these functions, the equivalent strut model developed by Smith [8] was used. Firstly, the effect of certain parameters on the damageability of brick infills was investigated by modeling several brick infills with a variety of properties. The parameters investigated within the scope of this study were the modulus of elasticity (E_m) and compressive strength of the infill material (f_m), geometry of the infill panel, concrete strength (f_{ck}) and flexural rigidity (EI) of the surrounding columns.

The equivalent strut model developed by Smith, like most of the other models available in the literature, is an elasto-plastic model that fails when a certain deformation limit is exceeded. The most important point on an elasto-plastic load deformation curve is the yield point (the point where the stiffness of the element becomes 0). This point can be defined by using the initial stiffness and yield strength of the element. The initial stiffness of a strut element is given as:

$$k = \frac{E_m t w}{d} \tag{5}$$

where t and d are the thickness and diagonal length of the infill panel, respectively, and w is the equivalent strut width. Of these terms, the first two are the geometric parameters of the infill panel and are easy to determine; whereas the determination of the equivalent strut width is arduous. Smith proposes the expression given in Equation 6 for the calculation of the equivalent strut width.

$$w = 0.175(\lambda h)^{-0.4} d \tag{6}$$

In Equation 6, h is the height of the infill and λ is a dimensionless parameter computed as:

$$\lambda = \sqrt[4]{\frac{E_m t \sin 2\theta}{4EIh'}} \tag{7}$$

where h' is the clear story height.

For the yield strength of the equivalent strut model, Mainstone [9] proposes two expressions. One of these expressions is for the case where the infill panel fails through compressive crushing, and the other one is for the diagonal shear failure of the infill. Mainstone [9] states that, the expression which gives the smaller failure load for an infill panel should be used as the yield strength of the equivalent strut. As a result of the studies carried out, it was observed that the expression for the diagonal shear failure of the infill was the critical one for all of the infills modeled. Thus, this expression, which is believed to represent the majority of the infills practiced in Turkey, was used in the development of the damage curves, and will be given here (Eq. 8)

$$N_y = \frac{\tau_o}{1-\mu(h/l)} dt \tag{8}$$

where N_y is the yield strength of the equivalent strut, τ_o is the shear strength of the infill material (can be taken to be equal to 3% of the compressive strength of the infill; τ_o=0.03f_m), μ is the coefficient of friction (can be taken as 0.3 for practical purposes), and *l* is the bay width.

Having computed the initial stiffness and the yield strength, the yield drift of the equivalent strut model can easily be computed as the ratio of the yield strength to the initial stiffness. The yield point can be taken as the point where the first major crack occurs in the infill panel. Brick infills are brittle materials, of which plastic displacement capacity is very limited. The infills can be assumed to be undamaged before the formation of the first major crack. However, as soon as this crack forms, the stiffness of the infill panel decreases drastically. The drift level at which the first major crack forms (i.e. the yield drift level of the equivalent strut model) can be taken as the lower limit of the heavy damage. In other words, the yield drift of the equivalent strut model is assumed to correspond to a damage score of 50% according to the damage criterion used herein. From that point on, the damage level of the infill increases drastically till complete failure.

The closed-form solution for the yield drift level indicates that the major parameters that affect this term are the compressive strength (f_m), diagonal length (d), modulus of elasticity (E_m) and height (h) of the infill panel. The yield drift of the equivalent strut is directly proportional to first two of these parameters, whereas it is inversely proportional to the remaining two. Since the damage criterion used is based on the yield drift, the damage score of the infills is affected significantly with the variations in the yield drift. In the light of this discussion, the infills were grouped into four based on their (f_md)/(E_mh) values. Then, the data point for these groups were plotted and damage functions similar to the ones given in Equations 1 and 2, except that both C_s and C_{fy} are both equal to 1.0, were developed for each group of the infills. The damage curves developed for the brick infills are presented in Figure 9.

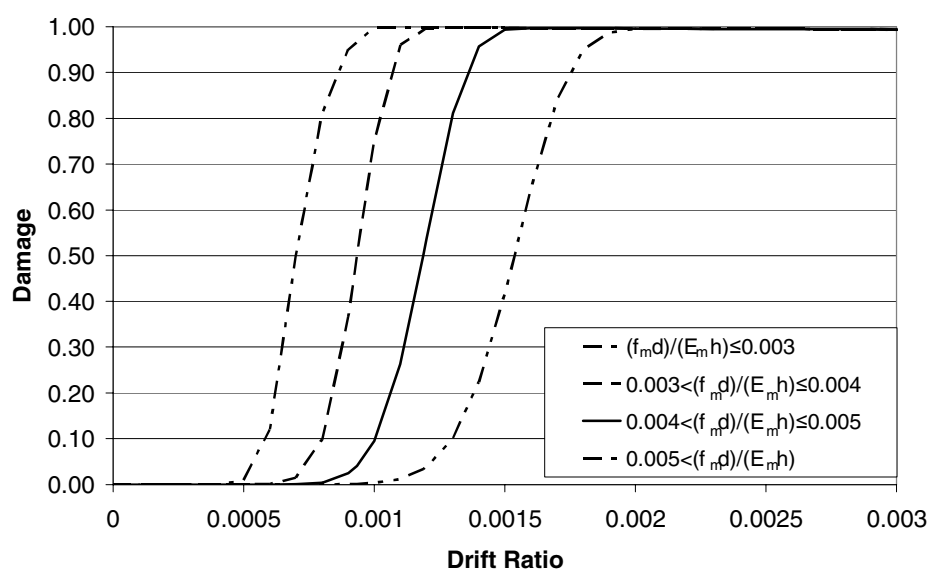


Figure 9 – Damage functions for brick infills

COMPONENT IMPORTANCE FACTORS

One of the most challenging parts of the component based vulnerability assessment is to combine the damage scores of the individual components to come up with a single damage score for the entire building. The most appropriate way for combining the component damage scores seems to be using the weighted average of them. For this, the weighing coefficients, which are named as component importance factors, must be determined. It is obvious that, the component importance factors will differ for the type of the component. Moreover, the importance factors of the components of the same type may differ according to their location in the structure. For instance, it is obvious that first story columns are far more important than the uppermost story columns in a medium rise building. To overcome this challenging problem, the procedure that will be summarized in the following paragraphs was developed.

In the seismic behavior of a structure, one of the most important points is the energy dissipation capacity of the structure. The greater the energy dissipation capacity is the higher is the chance of survival of the structure. Based on this fact, the energy dissipation capacity was selected as the criterion in determination of the component importance factors. The first step of the developed procedure is the nonlinear static analysis (pushover analysis) of the structure. Then, the energy dissipated by the structure is computed by summing the areas under the story drift – story shear force curves of each story and named as E_o. As the next step, a series of modified models is obtained by introducing damage to the components of each type at each story. For an n story structure, the number of modified cases will be 3n (n cases to designate damaged columns of each story, n cases to designate damaged beams of each story and n cases for the infills). For instance, to designate the damage of the columns of a story, the moments at the ends of all but exterior columns of the story are released to represent the plastic hinges forming during the earthquakes. Then, a pushover analysis was carried out and the energy dissipated by each damage case is computed and named as E_i. The ratio of the energy dissipated by a damage case i,, E_i, to the energy dissipated by the virgin structure, E_o, is an indicator of the importance of the component that was assumed to be damaged in that particular case. For an n story building, the importance factor of one component type of a story is computed as:

$$IF_i = \frac{E_i / E_o}{\sum_{i=1}^{3n} (E_i / E_o)} \tag{9}$$

By this way, the importance factors for columns, beams and infills of all the stories are computed for a single structure. Here it must be noted that the importance factors computed in this manner do not belong to a single member, but they reflect the importance of the members of the same type of a whole story.

Once the component damage curves and the corresponding importance factors are obtained, then the maximum drift at each floor for a given earthquake is determined. The drift ratios are then used to compute qualitative damage grades of each component in the given building. These damage scores are combined using component importance factors to obtain a corresponding global damage score for the building as a whole. The intensity of the given earthquake plotted against the calculated damage score yields a point for the damage curve of the building. The same procedure repeated for a range of earthquakes intensities results in adequate number of points to form a complete damage curve. For the earthquake intensity, among the several parameters used in the literature the spectral displacement is adopted here.

CONCLUSIONS

Predicting the seismic vulnerability of a reinforced concrete structure is not an easy task due to lack of experimental and empirical data. However, several researches have been carried out on the behavior of the components of RC structures resulting in considerable data on the behavior of these components. Thus, assessing the seismic vulnerability of RC structures based on its components seems more feasible. In this context, research had been carried out to develop damage functions for the components of RC structures based on interstory drift ratio.

There are several parameters that affect the behavior of columns, beams and brick infills. As a result of the numerical studies carried out, it was observed that the most significant parameters affecting the damageability of RC columns are the yield strength of longitudinal reinforcement, slenderness of the column, axial load level and level of confinement. Moreover, it was shown that concrete strength and amount of longitudinal reinforcement greatly influence the level of lateral load capacity, but has no significant effect on the deformability of RC columns. For the beams, the most significant parameters that must be taken into account are the depth of the beam, yield strength and amount of longitudinal reinforcement (both compression and tension reinforcement), and concrete strength. The significant parameters affecting the damageability of brick infills are the strength, and Young's modulus of the infill material and the geometry of the infill panel. The curves developed take the effect of the significant parameters into account.

In the component based vulnerability assessment, one of the most important points is the determination of the weighing coefficients that would be used in combining the damage scores of members to come up with a single damage score for the entire structure. A procedure was developed for the determination of the component importance factors. This procedure mainly depends on the contribution of the components to the energy dissipation capacity of the structures.

ACKNOWLEDGEMENTS

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