DETERMINING INTERSTOREY DRIFT CAPACITY OF R/C FRAME BUILDING

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ABSTRACT :

In most current seismic codes the criterion of whether the performance objective for a certain level of behaviour has been met is usually given by means of seismic response parameter defined at the level of the storey such as the maximum inter-story drift ratio IDR_{max}. On the other side, in order to estimate the colapse state for structures exposed to strong earthquake motions which apart from the elatic domain enter also in to the plastic domain of behaviour, it is necessary to know also deformations capacity at the places of plasticity, i.e. capacity of plastic hinges θ_{max}. This paper will show a method of determining capacity IDR_{max} by means of local parameters of seismic response: plastic rotation capacity, θ_{pu} and damage index, DI. The relations between IDR_{max} on one side and θ_{pu} and DI on the other are established by means of non-linear dynamic analyses of 4, 6, 8 and 12- storey RC frames designed according to the EC8.

KEYWORDS: capacity, maximum inter-story drift ratio, reinforced concrete frame, damage index

1. INTRODUCTION

Today the real seismic safety degree of a structure can be obtained by comparing the calculated seismic response of a selected deformation parameter with its capacity. The most frequently applied parameter of response is the maximum inter-storey drift ratio, IDR_{max}, where the storey drift ratio implies the relative storey displacement divided by the storey height. Paper (Jankovic, 2005) shows the procedure for determining IDR_{max} capacity by means of the so called incremental dynamic analysis, IDA, where the notion capacity implied the value of IDR_{max} when the structure loses global stability. This paper will show the method of determinig IDR_{max} capacity by means of the local seismic response parameters: plastic rotation capacity, θ_{pu} and damage index, DI. The relations between IDR_{max} on one side and θ_{pu} and DI on the other side are established by non-linear dynamic analyses of 4, 6, 8 and 12- storey RC frames designed according to the (EC8, 2008).

2. LOCAL PARAMETERS OF SEISMIC RESPONSE

It can be assumed, on the condition of good details of reinforcement of potential plastic hinges, that the maximum rotation capacity θ_{pu} will directly depend on the ultimate compression strain of the concrete ε_{cu} , i.e. that it will reach ε_{cu} before the longitudinar bars fracture (whether by break of by buckling) or break of the transverse reinforcement. These assumptions are usually met in reinforced concrete elements designed according to the new seismic codes such as the EC8. In this paper the value for ε_{cu} has been caluculated by taking into account the influence of transversal reinforcement on concrete confinement, and in all according to (Mander et al., 1988).

By using the moment – curve analysis, conducted using the program USFyber (Chadwell, 2000), it is possible to find the plastic curve capacity of transversal sections of beams and columns of RC frames, $\varphi_{pu} = \varphi_u - \varphi_y$ where φ_u is the curve which corresponds to the achievment of ε_{cu} and φ_y is yield curve. In order to determine now the plastic rotation capacity $\theta_{pu} = \theta_u - \theta_y$, it is necessary to multiply the obtained curve φ_{pu} with the plastic hinge length l_p. Here the half-empirical formula proposed in (Paulay, Priestley, 1992) is used for l_p:

$$l_p = 0.08l + 0.022 d_b f_y \quad \text{(MPa)} \tag{2.1}$$

where: l – is the length from section with the maximum moment up to the inflexion point, d_b – is the reinforcing bar diameter, f_y –is the yield stress of longitudinal reinforcement (in MPa).

The damage index, DI represents the quantitative measure of construction and/or non-construction element and/or structure damage. Numerous proposals have been put forward to day in scientific papers for the damage index, whose state-of–the-art review can be found in the paper (CEB State-of-the-Report, 1996). Damage indices, DI can have values between the limits: 0 for the state without damage and 1 for the limit state or failure and they can refer to elements (local DI) or to the entire structure (global DI). DI can be based on non-reversible (i.e. plastic) deformations, forces or dissipated energy. DI defined here is based on plastic deformations, both the maximum and the cumulative ones and it characterizes only the constructive and local damages. Namely, the latest research work has shown that cumulative plastic deformations considerably better include the basic fracture mechanisms than the dissipated energy or forces (strength).

In this paper damage index, DI has been adopted in the form of the formula:

$$DI = \sqrt[\gamma]{\left(DI_\theta^+\right)^\gamma + \left(DI_\theta^-\right)^\gamma} \tag{2.2}$$

Where damage indices for positive and negative rotations of plastic hinges are given separately with:

$$DI_\theta^+ = \frac{\left(\theta_{p,max}^+\right)^\alpha + \left(\theta_{p,kum}^+ - \theta_{p,max}^+\right)^\beta}{\left(\theta_{p,u}^+\right)^\alpha + \left(\theta_{p,kum}^+ - \theta_{p,max}^+\right)^\beta} \quad \text{for positive deformations} \tag{2.3}$$

$$DI_\theta^- = \frac{\left|\theta_{p,max}^-\right|^\alpha + \left(\theta_{p,kum}^- - \left|\theta_{p,max}^-\right|\right)^\beta}{\left|\theta_{p,u}^-\right|^\alpha + \left(\theta_{p,kum}^- - \left|\theta_{p,max}^-\right|\right)^\beta} \quad \text{for negative deformations} \tag{2.4}$$

Here, the values are following:

$\theta_{p,\max}^+$ - current maximum positive plastic rotation

$\theta_{p,kum}^+$ - current maximum cumulative positive plastic rotation

$\theta_{p,u}^+$ - plastic rotation capacity at monotonous loading in the positive deformation direction

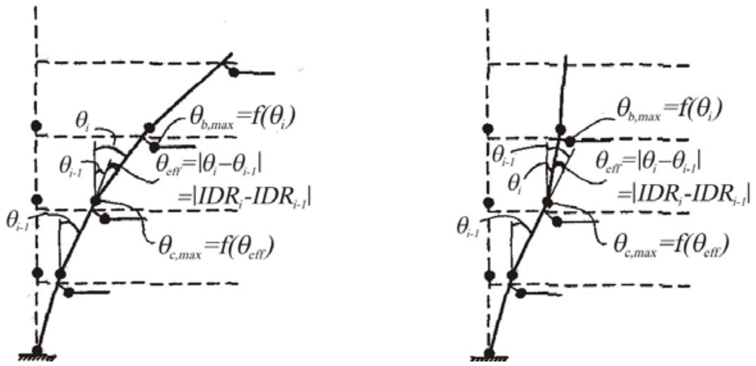
α, β i γ - calibration parameters

For negative deformations similar definitions are valid but absolute values are taken for the calculation. Calibration parameters are obtained by calibrating the given equation with the experimental data and for reinforced concrete elements the following values were obtained: α = 1.0, β = 1.5 and γ = 6.0, (Mehanny, 2000).

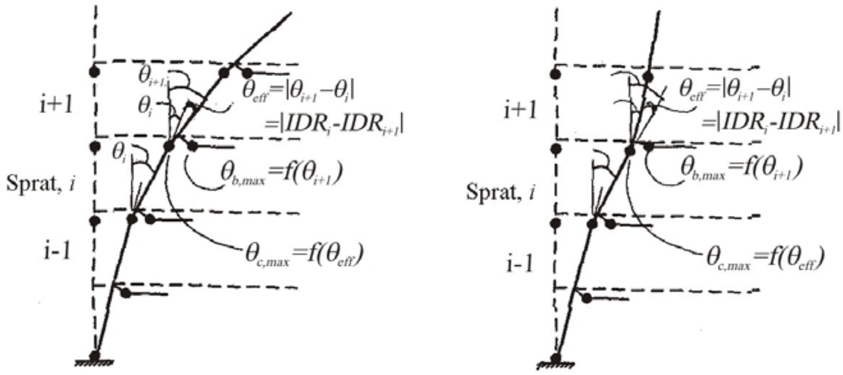
In defining of DI the paper (Mehanny, 2000) was used. It should be said however that Eqn. 2.3 and Eqn. 2.4 represent the original proposal for defining DI and that index defined in such a way gives identical results for DI during loading as Mehanny's proposal but it is at the same time simpler and easier for calculation.

3. RELATION BETWEEN STOREY AND LOCAL PARAMETERS OF SEISMIC RESPONSE

Figure 1 shows different forms of deformations of RC frame structures during earthquakes for the case when plastic hinges are formed at the lower end of the column of the considered storey (Figure 1(a)) and for the case when plastic hinges are formed at the upper end of the column of the considered storey (Figure 1(b)).



(a) Forming of plastic hinges at lower ends of columns



(b) Forming of plastic hinges at upper ends of columns

Figure 1 Schemes of various deformation forms of RC frames, (Mehanny, 2000)

For the case of plastic hinges formation at the upper end of columns on the considered storey it can be observed that the maximum plastic rotation in the column $\theta_{c,max}$ is best represented through difference between IDR of the considered storey and IDR of the storey above, marked with ΔIDR, i.e. $|IDR_i - IDR_{i+1}| = \Delta IDR$. Also, for the case of the same frame deformation configuration the maximum plastic rotation in the beam $\theta_{b,max}$ can best be compared with the IDR of the storey above. Reasons for the establishment of the proposed relations can be seen in Figure 1(a), according to (Mehanny, 2000) for two configurations of RC frame deformation. The angle of column slope on the storey i in relation to the vertical is marked by θ_I in figures, which is approximately equal to IDR_i (for small values angle tangent is equal to the very angle). In distinction from this case, Figure 1(b) shows that when plastic hinges appear at the lower ends of columns, the relation can be established between $\theta_{c,max}$ and the difference between IDR of the considered storey and IDR of the storey below, i.e. $|IDR_i - IDR_{i-1}| = \Delta IDR$, and between $\theta_{b,max}$ and IDR of the same storey.

Based on the above the following form of relations between the local and the storey parameters of seisimic response can be established:

$$\theta_{c,\max} = f\left(|IDR_i - IDR_{i+1}| \quad ili \quad |IDR_i - IDR_{i-1}| \right) = \alpha \cdot \Delta IDR + \beta \qquad (3.1)$$

$$\theta_{b,\max} = f\left(IDR_i \quad ili \quad IDR_{i+1} \right) = \alpha \cdot IDR + \beta \tag{3.2}$$

With the assumed linear regression analysis (because as such it gave the best correlation coefficient marked with *R*) the obtained results were fitted and the coefficients α and β which exist in Eqn. 3.1 and Eqn. 3.2 were determined.

4. ANALYSES RESULTS

Figure 2 gives, for all analysed frames, pairs of maximum plastic rotation in the beams of one storey, θ_{pu} and IDR_{max} of the considered storey or of the storey above depending on whether the maximum rotations of plastic hinges in columns were bigger at the upper or the lower end. It is evident that a linear function can be established between these two response parameters with a very high square of correlation coefficient, thus the following was obtained: $R^2 = 0.856$, $R^2 = 0.951$, $R^2 = 0.946$ and $R^2 = 0.989$ for 4, 6, 8 and 12-storey RC rames respectively. Also, very small disperson values σ were calculated too (standard deviation of natural logarithms of difference between the obtained results and the regression line). These results were obtained by non-linear dynamic analyses, using the program DRAIN-2DX (Prakash et al., 1993), of RC frames during 20 earthquakes taken over from (Ambraseys et al., 2000), scaled with factors 6 and 12 which correspond to the intensities with probabilities of exceedance of 2% and 10% in 50 years, while all the responses of the system in the elastic domain in which plastic rotations were equal to zero were omitted.

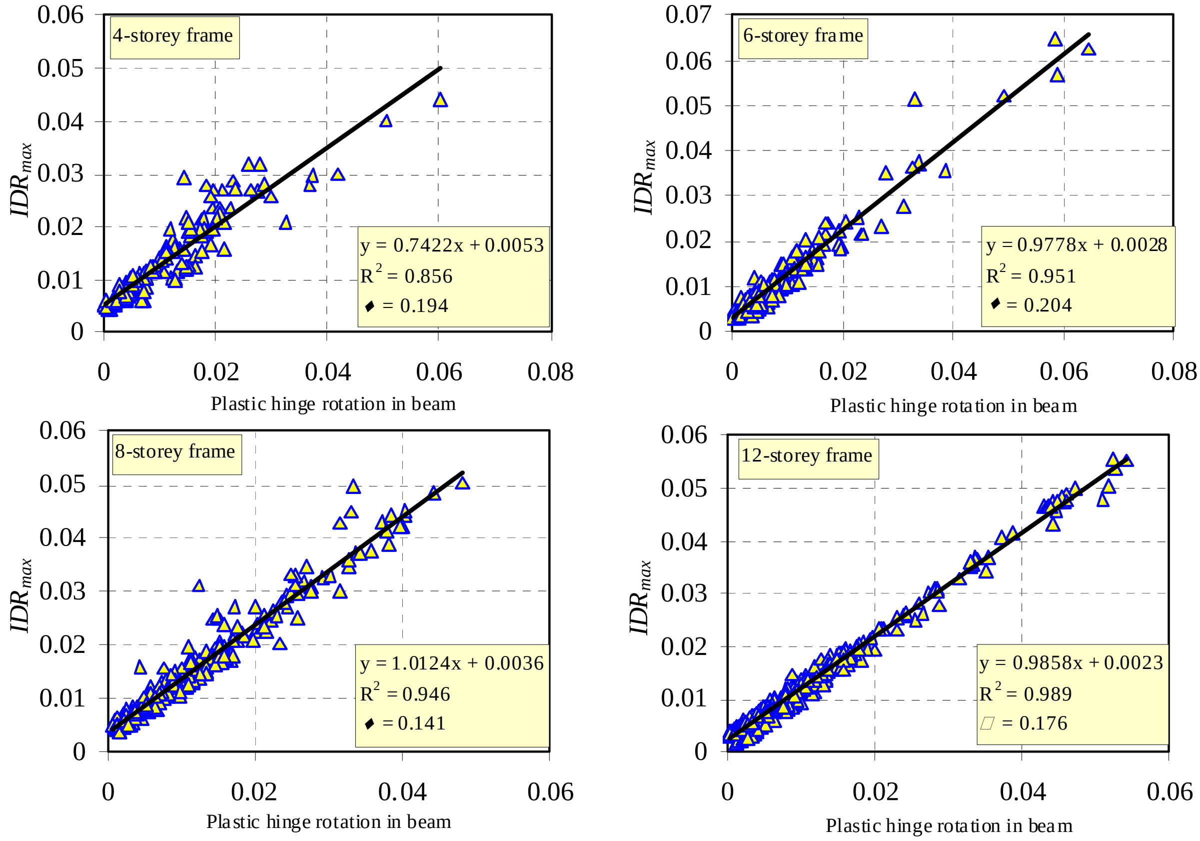


Figure 2 The relation between the maximum plastic rotation in beam, θ_{pu} and the maximum storey drift IDR_{max} for 4, 6, 8 and 12 storey RC frames, under 20 earthquakes of 10%/50 intensity and 20 earthquakes of 2%/50 intensity

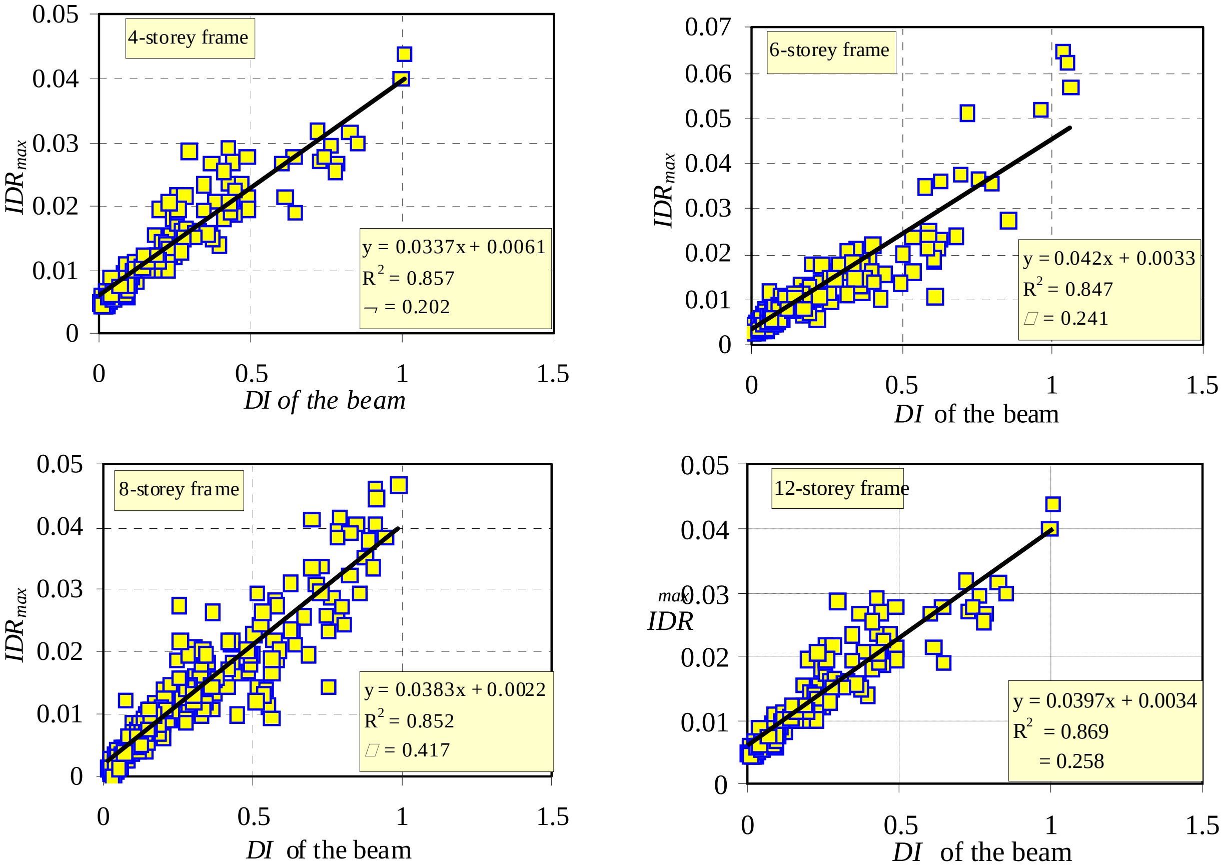


Figure 3 The relation between the damage index in beams, DI_b and the maximum storey drift IDR_{max} for 4, 6, 8 and 12 storey RC frames, under 20 earthquakes of 10%/50 intensity and 20 earthquakes of 2%/50 intensity

Intersection of the regression line and Y-axis can actually be considered as IDR due to elastic deformations i.e. such story drift which will not cause any plastic deformations. This IDR for the analyzed frames was: 0.53%, 0.28%, 0.36% and 0.23%.

Figure 3 shows pairs of damage indices in beams, DI and the maximum storey drifts IDR_{max}, where it is evident that in distinction from dependencies shown in Figure 2 the slope of the regression line here is smaller. Such a reduced slope of the regression line is the consequence of cumulative damages included in DI. Namely, by increasing IDR_{max}, DI in relation to θ_{pu} grows significantly faster, because apart from maximum plastic rotations parameter DI includes also cumulative plastic rotations which are more expressed in stronger earthquake intensities.

Based on dependencies and regression lines established in such a way between the local and storey parameters of seismic response the maximum capacity IDR_{max} which corresponds to the state of collapse (i.e. which corresponds to the value DI = 1.0) can be determined. Table 4.1 includes values for the IDR_{max} capacity which based on the regression lines shown in Figure 3 correspond to the value DI = 1.0. The same Ttable shows also values of IDR_{max} capacity which correspond to the average capacities of plastic hinges rotations θ_{pu}. Degree of influence of cumulative damages on the storey drift capacity IDR_{max} can be concluded based on the comparisons of its values obtained by taking (IDR_{max} which corresponds to DI =1) and neglecting the cumulative damages (IDR_{max} which corresponds to θ_{pu}).

Table 4.1 Storey drift capacity IDR_{max}

Frame	4-storey	6-storey	8-storey	12-storey
θ_{pu}	0.0694	0.0669	0.0687	0.0684
IDR_{max} for θ_{pu}	5.68%	6.82%	7.32%	6.97%
IDR_{max} for DI=1	3.98%	4.53%	4.05%	4.31%

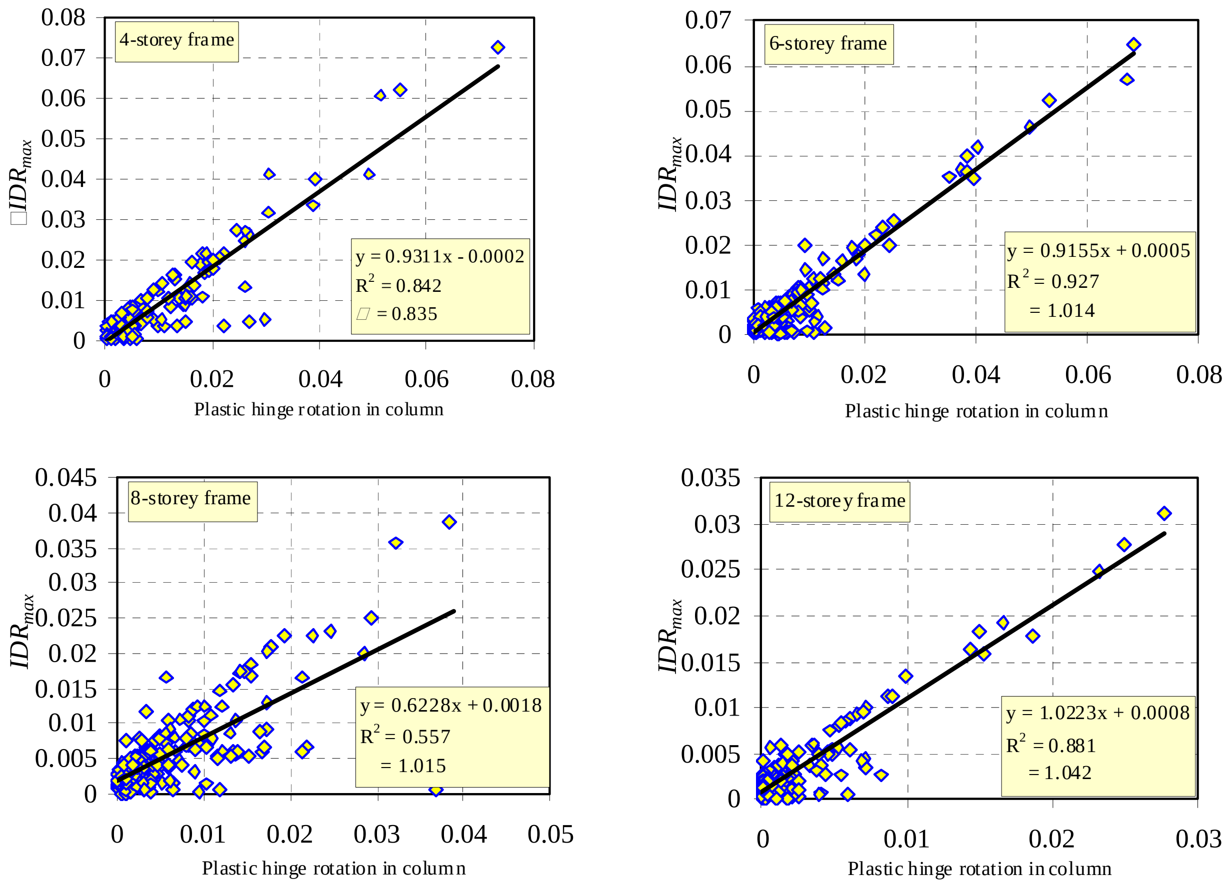


Figure 4 The relation between the maximum plastic rotation in the column, $\theta_{c,max}$ and the difference of maximum story drifts of neighbouring storeys ΔIDR_{max} for 4, 6, 8 and 12 storey RC frames, under 20 earthquakes of 10%/50 intentsity and 20 earthquakes of 2%/50 intensity.

Figures 4 and 5 show pairs of maximum plastic rotation in the columns of one storey, $\theta_{c,max}$ and differences of maximum drifts of neighboring storeys ΔIDR and pairs of damage indices in the columns, DI_c and ΔIDR. Since under earthquakes plastic hinges formed both at the lower and at the upper ends of columns (which does not mean simultaneously), the maximum storey drift ΔIDR represents the difference of drift of the considered storey and the storey above when the maximum plastic rotation on the upper end of the column is bigger than the maximum plastic rotation at the lower end of the columns.

Dispersion of results is noticeably bigger in these figures than in the relations shown in Figures 2 and 3. Fortunately, the establishment of relation between the local, plastic deformations in the column and storey drifts is much less significant than the relation between the plastic deformations in beams and storey drifts. Namely, beam flexibility will mostly influence storey displacement since beams' span usually exceeds the storey height and the curves in the column are smaller than those in the beam as a result of the capacity design use in EC8.

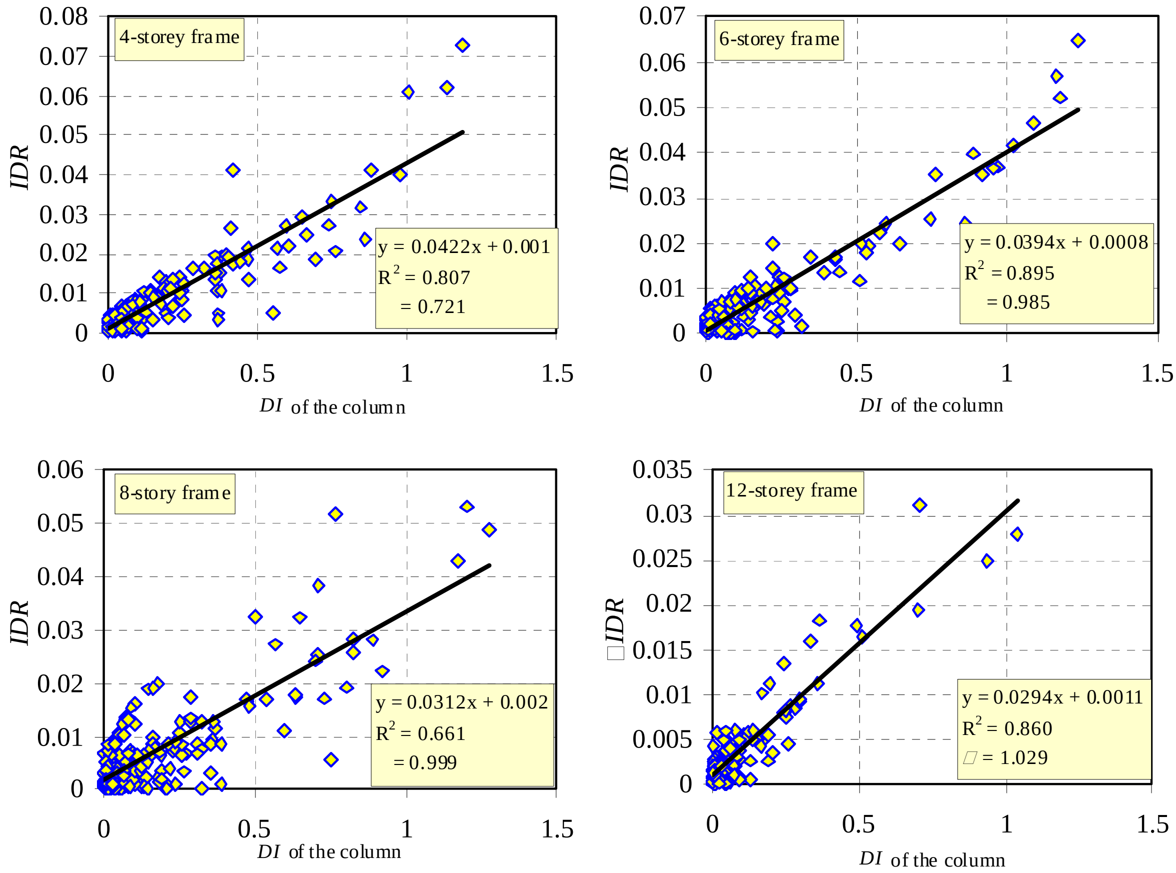


Figure 5 The relation between damage index in the columns, DI_c and the maximum story drifts difference of neighbouring storeys ΔIDR for 4, 6, 8 and 12 storey RC frames, under 20 earthquakes of 10%/50 intensity and 20 earthquakes of 2%/50 intensity.

5. CONCLUSION

In this paper relations were established between local parameters of seismic response (plastic rotation and damage index), in RC frames with different numbers of storeys, and seismic response parameters at the storey level (maximum inter-storey drift ratio, IDR_{max}). It was shown that good correlation can be established between plastic rotation and beam damage index and IDR_{max}. Not only can the obtained relations serve for obtaining one parameter of response in case when the other one is known, but they have been used to calculate the IDR_{max} capacity using the ultimate values of local parameters, plastic hinges rotation and damage index. In this way capacities of IDR_{max} were calculated where the influence of cumultive damages (included in the damage index) on reduction of the IDR_{max} capacity can also be seen. The obtained values of IDR_{max} capacity ranged approximately between 4.0% and 4.5%. Also, when using the probabilistic format of seismic analysis of structures, the obtained relations can be used for determining conditional probability that a certain local response will be exceeded for the given story parameter of seismic response IDR_{max}.

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