A NEW APPROACH FOR THE PRELIMINARY SEISMIC ASSESSMENT OF RC BUILDINGS: P25 SCORING METHOD

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ABSTRACT :

The need for vulnerability assessment of urban scale building populations is of increasing interest due to the high seismic risk in densely populated areas around the world. Istanbul, Turkey, is one of the most intensively populated metropolises in the world in addition to being probably one of the most risky cities in terms of the expected seismic activity in the near future. In order to minimize the seismic risk of the city, instead of the method of evaluating every single building according to the existing code which failed immediately due to the source and time limitations, a wiser approach is being employed nowadays, namely, evaluating each building in the stock by using some simplified rapid or preliminary assessment techniques and focusing primarily on the "collapse vulnerable" structures. The proposed P25 Scoring Method is a preliminary assessment approach which is primarily based on calculation of area and inertia based ratios of structural members and infill walls as well as on observing and listing the most important structural parameters which affect the seismic response of a building. The method has been calibrated with 323 RC buildings from different seismic regions of Turkey that are subjected to different past earthquakes and experienced various levels of damages. The damage states and also performance levels of the analyzed case study buildings are found to be in good agreement with the proposed primary assessment technique. The paper includes the details of the method and the calibration results.

KEYWORDS: Preliminary assessment, rapid screening, collapse vulnerability, seismic risk

1. INTRODUCTION

The usual procedure to determine seismic safety and performance level of existing buildings is to perform a 3D computer analysis of structural systems by linear or non-linear approaches according to the relevant codes; however, such an approach would entail unprecedented difficulties when an urban scale mitigation campaign is considered. For instance, it would be almost unaffordable in terms of cost and time needed. Furthermore, the legal disputes among the property owners of the condominiums, as to the necessity, type and extent of the retrofit, would be insurmountable. This procedure is rather difficult and even impossible when the size of the building stock is large and the limitations on timing and sources are many as in a metropolitan area like Istanbul, where a large earthquake is expected in the near future. As a consequence, minimization of the number of buildings which will totally collapse and cause loss of life became the main target of engineers and scientists. It appears to be a wiser approach to use detailed assessment procedures and limited sources on *"collapse vulnerable"* structures which will be detected by applying some practical, economical but yet reliable rapid screening or preliminary assessment techniques which do not require heavy analytical work. The main idea behind identifying such *'collapse vulnerable'* buildings is to assess them in a more detailed and accurate manner following this elimination procedure and seismically retrofit or demolish them prior to a future destructive earthquake in order to avoid excessive losses of life. Concept of "zero loss of life", national strategies that should be followed to achieve this target, financial and logistic issues related to these strategies are first discussed by Tezcan et al. (Tezcan and Gürsoy, 2002; Tezcan and Bal, 1004 and 2005).

In order to establish a common terminology, some essential definitions are given by the authors as following: What is called hereinafter as *"rapid screening methods"* are the first step applications which are applied as walk-down survey where entering of engineers the subject building is not needed. The *"preliminary assessment"* methods are applied as a quick survey but it is necessary that a team of engineers enter the subject building and take some measurements and conduct in-situ tests inside the building. The third step is the *"detailed assessment"* procedure defined by the relevant code. Main idea is to decrease the number of vulnerable structures in each step and reach the target group at the end; however, authors do not suggest the use of the first step since it can be completed during the execution of the second step and it does not have much of application as far as the Turkish building stock is considered. It should be noted that *P25 Scoring Method* proposed herein corresponds to the second group which is called as *"preliminary assessment"* techniques.

Many researchers work on alternative methods to define the collapse risk of existing buildings by using certain parameters of which affects on the response of RC buildings have been observed during the recent earthquakes. A rapid screening method was first proposed with ATC 21 ve ATC 21-1 to be applied prior to detailed assessment (FEMA 154, 1988-2002 and FEMA 155, 1988). Other methods, which are preliminary assessment techniques, have also been proposed, indicatively, McCormack and Craig (1996), and Hassan and Sözen (1997). Japanese Seismic Index Method is another preliminary assessment technique that was originally developed for Japan (Ohkubo, 1990) and then modified for Turkey (Boduroğlu, 2004).

Expected large scale earthquake right in front of the densely populated mega city of Istanbul obliges the authorities to take some urgent measures to save the population from a near disaster. Rapid and preliminary assessment methods are also being heavily employed by the local authorities in Istanbul along with other mitigation measures. The sole aim of these techniques is to identify rapidly the collapse vulnerable buildings existing within a large building stock and to make local authorities to be able to focus their limited time and sources to *"the worst percentage"*.

The recent approach named as *'P25 Scoring Method'* which primarily aims to identify collapse-vulnerable structures has been developed and applied to the database of many buildings which were damaged in earlier earthquakes in Turkey. The method has been proposed initially by Bal (2005) and then developed and calibrated through a research project supported by TUBİTAK. For the calibration purposes the method is applied to 323 RC buildings with different damage states, located on different soil conditions and subjected to various seismic actions during the recent earthquakes in Turkey, (Bal et al., 2006a). Parameters such as pounding, short column, corrosion, mass irregularity etc. have been calibrated by means of analytical studies, also. Some representative buildings from the stock have been analyzed in order to compare the code-based assessment results with P25 preliminary assessment outcomes. The method has been applied to a pilot region in Istanbul and the obtained experience has been described in the research work. Briefly, a safe and an applicable solution method, P25, has been suggested to be used for defining the collapse vulnerable structures of the intensive building stock of large metropolitan areas, like Istanbul, to be utilized for the mitigation works for the expected seismic actions (Gülay et al., 2008a).

2. BASIC FEATURES OF P25 SCORING METHOD

The method is primarily based on observing and listing the most important parameters which affect the seismic response of a building. These parameters are then scored with relevant weighting factors in relation to their relative importance. Seven different scores for corresponding failure modes, P_1 to P_7, and their interactions are considered. The final performance score *"P"* of the building is an amalgamation of these seven scores which is graded between 0 and 100, varying from the worst to the best, respectively.

2.1 Calculation of the basic score: P_1

For the building stock in Turkey and in most of other countries, the most collapse vulnerable storey is generally the ground floor, which is called as the *'critical storey'* in this approach. However, some exceptions to this rule may obviously exist. Thus, to be on the safe side, all other possible critical storey alternatives should also be checked and the storey which results in the smallest score should be accepted as the *'critical storey'* of the building.

Plan dimensions L_x and L_y are the x and y-sides of the smallest rectangle into which the plan of the critical storey may be placed. Thus, the buildings with irregular plan dimensions will be penalized in scoring since a relatively larger plan area instead of the actual one is considered and this results a lower score for the building. Eventually, for the critical storey, the gross floor area A_p will be calculated as $A_p = L_x L_y$ and the gross moment of inertia I_{px} and I_{py} values will be calculated as $I_{px} = L_y L_x^3 / 12$ and $I_{py} = L_x L^3 / 12$.

The sums of the cross-sectional areas ($A_{ef,x}$) and the moments of inertias ($I_{ef,x}$) of columns, shear walls and masonry infill walls will be divided by the overall floor area A_p and moments of inertia I_{px}, I_{py} , respectively. This operation is applied to both x and y- directions and an effective statistical minimum values $C_{A,ef}$ and $C_{I,ef}$ are calculated as follows:

The effective rigidities in x- direction are calculated from

$$C_{A\,x} = 2\,(10^5)\left(\sum A_{ef,x}\right)/\,A_p \qquad (2.1)$$

$$C_{I\,x} = 2\,(10^5)\left[\left(\sum I_{ef,x}\right)/\,I_{p\,x}\right]^{0.20} \qquad (2.2)$$

in which,

$$A_{ef,x} = A_c + A_{sx} + (E_m/E_c)\,A_w \quad \text{and} \quad I_{ef,x} = I_{cx} + I_{sx} + (E_m/E_c)\,I_{wx} \qquad (2.3)\ \&\ (2.4)$$

where A_c is the cross-sectional area of a column, A_{sx}, A_{wx} are cross-sectional area of the RC shear wall, and infill masonry wall, respectively *(consider those extending in x-direction only)*, I_{cx} is the moment of inertia of a column about y-axis, I_{sx}, I_{wx} are moments of inertia of the RC shear walls, and infill masonry walls, about y-axis, respectively *(consider those extending in x-direction only)*, E_m/E_c is the ratio of the masonry modulus of elasticity to that of concrete where suggested values are 0.08 for adobe, 0.15 for clay brick with void, 0.20 for solid clay bricks, and 0.30 for concrete briquette.

The multiplier of $2(10^5)$ in Eqn.s (2.1) and (2.2) is just a simple scalar value which is used to obtain a better presentation of the scores in 0-100 scale. Furthermore, the power of 0.5 should have been added to the expression in Eqn. (2.2) since the order of magnitude of the cross-sectional area (2nd degree) values are much smaller than those of the moment of inertia (4th degree), in order to be able to use them in the same formula. However, it is known that the flexural behaviour is more dominant in most cases and this is the reason why the theoretical value of 0.5 is decreased to 0.2 in order to take the effect of the flexural rigidities more into account.

The effective resultant rigidity C_{Ar} of the cross-sectional areas and the effective resultant flexural rigidity C_{Ir} of the critical storey are calculated as *(units are in meters)* ;

$$\mathrm{C}_{\mathrm{A\,r}} = \left[\left(\mathrm{Cos}(\Theta)\mathrm{C}_{\mathrm{A,min}}\right)^2 + \left(\mathrm{Sin}(\Theta)\mathrm{C}_{\mathrm{A,max}}\right)^2\right]^{0.5} \qquad (2.5)$$

$$C_{I\,r} = \left[\left(Cos(\Theta)C_{I,\min}\right)^2 + \left(Sin(\Theta)C_{I,\max}\right)^2\right]^{0.5} \qquad (2.6)$$

where,

$$C_{A,\,min} = min\;(C_{A,x}\;;\;C_{A,y}), \qquad C_{A,\,max} = max(\,C_{A,x}\;;\;C_{A,y}\,) \qquad (2.7)$$

$$C_{I,\,min} = min(\,C_{I,x}\;;\;C_{I,y}\;\;), \qquad C_{I,\,max} = max(\,C_{I,x}\;;\;C_{I,y}\,) \qquad (2.8)$$

In Eqn.s (2.7) and (2.8) Θ is the smaller angle between the dominant direction of the expected earthquake and the weakest direction of the examined building. In case there is no available datum for angle Θ, it varies between 0 and 45 degrees since the most conservative approach could be to assume that the earthquake shear waves strike the building parallel to the weakest direction, or less conservative approach is that an average value of strong and weak direction rigidities responds to the earthquake. Most of the world-wide design codes assume a 30% contribution of the earthquake forces of the perpendicular direction, resulting Θ as 17 degrees. Following several trials with the dataset, it is suggested to assume the Θ angle as 30 degrees where the datum is not available.

For *x*-direction calculations, the RC shear walls and infill masonry walls extending in *x*-direction will be taken into account, and only the moment of inertia values about *y*-axis will be included in I_{sx} and I_{wx} calculations. Similarly, in *y*-direction, the RC shear walls and infill masonry walls extending in *y*-direction will be taken into account, and only the moment of inertia values about *x*-axis will be included in I_{sy}, and I_{wy} parameters.

2.1.1. Calculation of the basic structural score P_1

Once the effective resultant cross-sectional area C_{Ar} and the effective resultant flexural rigidity C_{Ir} of the critical storey are available from Eqs. (2.5) and (2.6), the bearing system score, P_0, and fundamental structural score, P_1, which relates most of the structural parameters of the examined building to the possible vulnerability, are obtained from:

$$P_0 = \left(C_{Ar} + C_{Ir}\right)/h_0 \tag{2.9}$$

$$P_1 = P_0\left(\prod_{i=1}^{14} f_i\right) \tag{2.10}$$

in which, h_0 is the height correction factor which is evaluated as explained at section *2.1.2* below , f_i represents *14* different structural correction factors related to various possible deficiencies of the building. They are obtained by quantitative means as outlined in section *2.1.3.* The P_1 score varies between 0 and 150, and rarely exceeds 150 in cases where the building follows modern design rules with minimum number of irregularities.

2.1.2. Normalization factor h_0 for height

The resultant rigidity parameter, $C_A + C_I$, is calculated independent of the total building height. As the number of storeys increases, the mass as well as the base shear will also increase. On the other hand, depending on the soil group, the base shear coefficient obtained from the response spectrum gradually decreases as the overall height of the building increases. Therefore, for low and medium rise buildings, the increase in height adversely affects the strength parameter P_1. For taller buildings however, the increase in height also has a favorable effect in the calculation of effective strength parameters. Considering all these variations, a suitable correction factor h_0, is proposed as seen in Eqn (2.11), which represents the effect of the building height. This correction factor results h_0=100 for a 3m-high, single storey building (nominal value) and becomes h_0=466 for a 5- storey building with H=15m. This formula has been obtained by generating around 9-thousand buildings having several different design input values. The change of h_0 with the total height of the building has been investigated for different span lengths (3-6m), changing from 1 to 12th storeys, having different storey heights (2.8m-3.7m) located on different soil profiles (rock, firm or soft). The parametric study was carried out for different concrete and steel types. The sample systems are designed for the old (1975) and the new (1998) earthquake Codes of Turkey. Details of this parametric study can be found in Gülay et al. (2008a). Thus , the final correction factor h_0 is given as $h_0 = -0.6H^2 + 39.6H - 13.4$ where H is the total building height in meters.

2.1.3. Structural correction factors - f_i

The corrections factors f_i including various structural irregularities, such as torsion, vertical discontinuity, slab discontinuity, staggered floors and structural details, material and soil properties etc. are used to take into account 14 different parameters which are assumed to affect the seismic response of the structure. Some of these correction factors are observational whereas some are calculated through small measurements and calculations after inspection of the structural project and the building in-situ. The calibration and verification of these values are made analytically on some sample real buildings through parametric studies of which details can be found in the final report of the TÜBİTAK research project (Gülay et al., 2008a). The corrections factors f_i are listed in Table 2.1.

2.2. Calculation of Short Column Score: P_2

If some columns are relatively shorter than the others in a given floor and they are not designed properly for the increased level of shear demands then they may cause non-ductile shear failure during a severe earthquake. There are 16 different scores for P_2, varying between *15* and *70* according to the Free Column Height / Storey Height ratios and ratio of the number of short columns to the total number of columns in a critical storey. Short column scores have been calibrated by cyclic pushover analyses and resulting dissipated energy values of sample real case study structures used for the parametric studies. Details of the analytical work are explained in the research report (Gülay et al., 2008a)

Table 2.1 Structural correction factors -f_i

Coefficient	Definition	Risk Level High	 Low	 N/A
f_1	Torsional Irregularity	0.90	0.95	1.00
f_2	Slab Irregularity	0.90	0.95	1.00
f_3	Vertical Irregularity	0.65-0.70	0.90	1.00
f_4	Mass Irregularity	0.75	0.85	1.00
f_5	Corrosion	0.80	0.90	1.00
f_6	Heavy Facade Elements	0.90	0.90	1.00
f_7	Sub-floors (γ=Sub-floor area / Floor Area)	0.90 $\gamma \geq 0.25$	0.95 $0 < \gamma < 0.25$	1.00 $\gamma = 0$
f_8	Staggered Floors or Partial Basement	0.80	0.90	1.00
f_9	Concrete Quality (1)	$f_9 = (f_c / 20)^{0.5}$		
f_{10}	Weak Column – Strong Beam (2)	$f_{10} = [(I_x + I_y) / 2 I_b]^{0.15} \leq 1.0$		
f_{11}	Stirrup Spacing (3)	$f_{11} = 0.60 \leq (10 / s)^{0.25} \leq 1.0$		
f_{12}	Soil Type	0.90 *(alluvium)*	0.95 *(firm soil)*	1.00 *(rock or stiff soil)*
f_{13}	Foundation Type	0.80 - 0.90 *(Pad / Footing)*	0.95 *(Strip Found.)*	1.00
f_{14}	Foundation Depth	0.90(<1m)	0.95(1-4m)	1.00(>4m)

(1) f_c is the compressive concrete strength in MPa.

(2) I_x, I_y values are the moments of inertia obtained by using average column dimensions in the critical floor. I_b is the moment of inertia of the most common beam in critical floor.

(3) s is the stirrup spacing in cm, around the confinement zones.

2.3. Calculation of Soft-Weak Storey Score: P_3

As it is well known from earlier experiences, the weak or/and soft storey deficiency can be the reason of a total collapse of the building. Weak storey is a type of deficiency which appears when the strength of the critical floor is much less than that of the upper floor. This is practically caused by lack of infill walls in the commercial ground floor. Soft storey is a stiffness problem which coincides with the weak storey problem in many cases due to the concern about creating a spacious commercial ground floor. Stiffness of the ground floor (or critical floor) is decreased significantly when the ground storey height is more than the regular storey height.

The soft storey score, P_3, is calculated from

$$P_3 = 100\left[r_a r_f \left(h_{i+1} / h_i\right)^3\right]^{0.60} \leq 100 \qquad (2.11)$$

where h_i and h_{i+1} values are the heights of the critical storey i and of the upper storey $i+1$, respectively and r_a and r_f are the cross-sectional area and flexural rigidity parameters, respectively, which are computed in both x and y-directions and the minimum values will be utilized:

$$r_a = \left(\sum A_{ef}\right)_i / \left(\sum A_{ef}\right)_{i+1} \le 1 \quad \text{and} \quad r_f = \left(\sum I_{ef}\right)_i / \left(\sum I_{ef}\right)_{i+1} \le 1 \qquad (2.12)\ \&\ (2.13)$$

$$A_{ef} = A_c + A_s + (E_m / E_c) A_w \quad \text{and} \quad I_{ef} = I_c + I_s + (E_m / E_c) I_w \qquad (2.14)\ \&\ (2.15)$$

2.4. Calculation of Overhangs and Frame Discontinuity Score, P_4

Being one of the most traditional characteristics of Turkish building stock, overhang is a structural feature which adversely affects the earthquake response of reinforced concrete buildings by changing the mass distribution, plan regularity, frame continuity thus the column bending moments. Since this outward offset concerns only the perimeter beams and not the perimeter columns, a slab section between the latter remains without beams, leading thus, partly or completely, to perimeter frames to consist of slab bands instead of proper beams. A numerical research on a number of buildings performed by Bal and Özdemir (2006b) showed a decrease in strength varying between 4% -50 %. Following this proposal P_4 score has been defined depending on the existence of the perimeter beams and on the onset of the overhang (i.e. at one side of the building, at two sides or more, etc.) varying between 50 and 90.

2.5.Pounding Score, P_5

The problem of pounding is particularly acute in many large cities located in seismically active regions where, due to land usage requirements, buildings are constructed near each other. The gap between the subject building and the adjacent building must be less than 1% of the total height of the shorter building in order to use the pounding scoring given in P25 Method; the pounding score P_5=100 will be assumed, otherwise. The suggested pounding scores P_5 are changing from 10 to 70 for possible combinations of 6 different types of pounding schemes, like concentric or eccentric pounding, with having same storey or different storey levels, including also the difference at the building heights and masses. More details on the calibration of pounding scores with nonlinear time-history analyses are given in Gülay et al. (2008a).

2.6.Soil Failure Scores, P_6 and P_7

The liquefaction score, P_6, is given between *10* and *60*, depending on the level of ground water table *(GWT)* and the calculated liquefaction risk potential to be as ‘low’, ‘medium’ or ‘high’. Soil bearing capacity failure score, P_7, varies between 10 and 100 depending on the soil type and depth of *GWT*. It should be noted that P_6 and P_7 scores are tentative and their values are not intended to represent a numerical value for soil failure. These values are more logic values which would lead, for instance, a building with high soil liquefaction or bearing capacity failure risk to be named as unsafe and to be eliminated according to the method.

2.7. Correction factor, α

The final score should be adjusted by means of a correction factor, α, defined in accordance with I, which is the value of building importance factor, A_0, the effective ground acceleration, n, the level of participation of live loads and t, the topographic effects , given as follows:

$$\alpha=(1/I)(1.4 - A_0)\,[\,1/(0.4n+0.88)]\,t \qquad (2.16)$$

The level of effective ground acceleration, A_0, varies between *0.10g* and *0.40g* for four different earthquake zones in Turkey. The live load participation factor, $n = 0.30$ for residential buildings whereas it is higher for other types of buildings. The correction for topographic effects, t, is assumed as *0.7* if the building is on top of a hill, while $t=0.85$ is used if the building is on a steep slope and $t=1$ for buildings on relatively flat regions. The increase in earthquake demand due to topographic effects has been based on two earlier studies (Sholtis and Stewart, 1999; Çelebi, 1987).

2.8.Correction factor, β

The correction factor β is calculated by considering the weighted interaction among seven parameters from P_1

to P_7. The minimum of these seven scores is considered as P_{min} and the weighting factor is assumed as $w=4$ for this minimum score. The suggested weighting factors for other scores are shown in Table 2.2. The weighted score, P_w, is calculated as;

$$P_w = \Sigma\,(w_i P_i) / \quad \Sigma\, w_i \tag{2.17}$$

Table 2.2. Weighting factor for P scores

Weighting	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_{min}
w	4	1	3	2	1	3	2	4

2.9. Calculation of the Final Score

The interaction correction factor, β, represents the degree of interaction and the possibility of triggering an interactive failure and is recommended, based on the value of the weighted score as follows:

$$\begin{aligned} &\beta = 0.70 \ldots\ldots\ldots\ldots & &\text{for } P_w \le 20 \\ &\beta = 0.55 + 0.0075\, P_w \ldots & &\text{for } 20 \le P_w \le 60 \\ &\beta = 1.00 \ldots\ldots\ldots\ldots & &\text{for } P_w \ge 60 \end{aligned} \tag{2.18}$$

The final score, P, is then calculated by selecting P_{min}= the smallest score among P_1 to P_7 as:

$$P = \alpha\, \beta\, P_{min}. \tag{2.19}$$

3. CALIBRATION RESULTS AND CONCLUSIONS

The method has been calibrated first with 126 RC buildings from different seismic regions that are subjected to different past earthquakes and experienced various levels of damages (Bal et al, 2006a), then it is applied to additional buildings and total number of buildings is increased up to 323 where 17 of these buildings were experienced total collapse during the recent earthquakes. Promising results are obtained when compared to real damages (Fig. 1). A recent study by Gülay et al. (2008b) has also examined two real buildings where one of them totally collapsed during recent earthquakes and the other has survived the same earthquake with negligible damage. These buildings were scored according to P25 Method and assessed according to the recent Turkish Earthquake Code of 2007. Results of the study show that real damage states are in agreement with the P25 results as well as with the detailed assessment findings. Details of comparison among real damage states, detailed assessment results and P25 scores of more case study buildings can be found in Gülay et al. (2008a). Studies show that, if P25 method had been applied to those example buildings before the earthquakes which they experienced, collapsed buildings would have been detected and they would be selected to be checked in detail by the detailed assessment methods while the buildings with slight damage would be eliminated from the target list.

Application of P25 Method on 323 real buildings show that the high risk band is between the scores of 15 and 35 and the performance score of 30 can then be considered as the safety-limit (Fig. 1). Buildings in high risk band are strongly suggested to be assessed in detail by expert engineers, and if necessary, they should be evacuated or retrofitted. The method is still in development stage and will be validated and updated as more additional data becomes available.

ACKNOWLEDGEMENTS

The authors would like to thank to UYGAR Center of İTU for providing 197 of 323 case study buildings. 75 of 323 buildings have been obtained from the METU building database (seru.metu.edu.tr). This study is financially supported by TÜBİTAK through the research project No: 106M278 and their generous support is gratefully acknowledged. Financial support by the Higher Education and Research Foundation is also acknowledged.

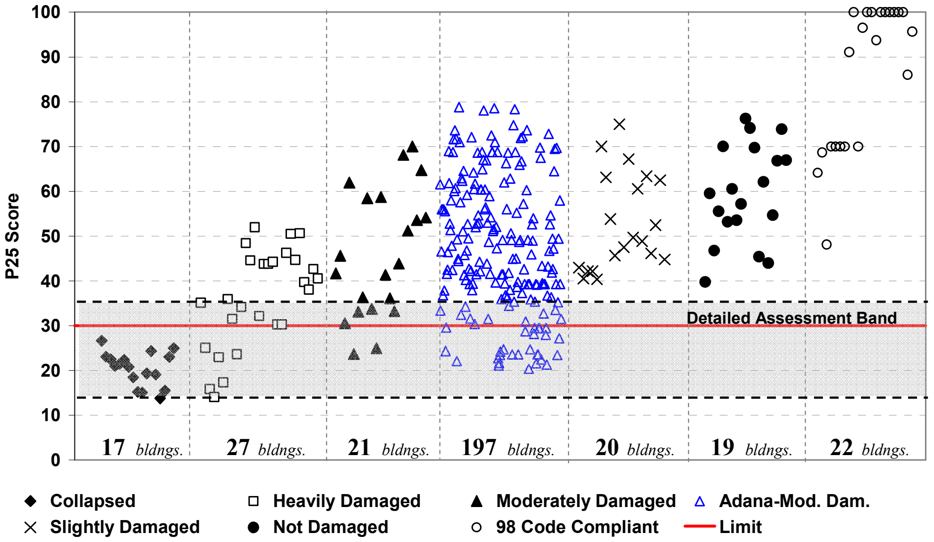

Figure 1 The results obtained with the application of the P25 Method on 323 real RC buildings

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