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A METHODOLOGY FOR DEVELOPING LOSS SCENARIOS, WITH AN APPLICATION TO THE CITY OF THESSALONIKI

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ABSTRACT

The present study addresses the problem of developing earthquake damage scenarios, including explicit estimates of loss in monetary terms. The key feature of the suggested methodology is the correlation of structural damage indices, derived with the aid of advanced analytical tools, to the cost of repair for each structural, as well as non-structural member of a building. The main output of the method is a "repair index" which expresses the required cost of repair as a fraction of the current value of the building. This index may then be used in deciding the type of intervention that should be implemented in each case. The methodology is applied in the case of Thessaloniki, Greece, and a complete damage scenario is developed, including the expected cost of repair of existing buildings when they are subjected to the design earthquake.

KEYWORDS

Earthquake damage scenarios; vulnerability analysis; loss estimate; repair of members; damage indices.

INTRODUCTION

A comprehensive methodology for developing earthquake damage scenarios for specific metropolitan areas involves the following basic steps (Kappos et al. 1992):

(i) Estimation of site-specific *design motions*, preferably in the form of acceleration time-histories.
(ii) Estimation of the *vulnerability* of various classes of structures, characterised by similar structural systems and materials; in its most refined version this estimation is carried out using advanced analysis tools, such as codes calculating the inelastic response of structures to input accelerograms.
(iii) Estimation of *losses* (in monetary terms) on the basis of the previously calculated vulnerabilities and the inventory of structures in the area under consideration. If an analytical procedure has been applied in the previous step, it is of paramount importance to establish an appropriate correlation between structural response quantities and corresponding loss parameters.

Steps (i) and (ii) above have been addressed in detail in previous studies by the authors (Kappos et al. 1991, 1992). The problem of vulnerability assessment using analytical techniques is discussed in detail by Kappos in the recent EAEE TG 3 Report (Dolce et al. 1995). Therefore, the present study will focuss on the third step, more particularly on the estimation of losses on the basis of structural response parameters selected from the output of analytical studies. Subsequently a brief reference will be made to an application of the foregoing methodology in the case of Thessaloniki (Macedonia, Greece).

SUGGESTED METHODOLOGY

The methodology described hereunder refers to buildings, more specifically to reinforced concrete (R/C) buildings; nevertheless several aspects of the methodology are also pertinent to other types structures. Although reference is made throughout to *"repair"*, it is understood that some of the techniques considered imply also *strengthening* of the structure.

General assumptions

(i) Buildings struck by an earthquake are classified into two basic categories:
  - Buildings that have failed (actual collapse or irrepairable damage); failure criteria appropriate for use in analytical studies are discussed by Kappos (1991). The loss in these buildings is taken equal to the replacement cost (with due account for depreciation, see next section).
  - Buildings with repairable damage, or no damage at all. In this case loss is expressed as a fraction of the replacement cost, calculated as described in the following.

(ii) The *cost of repair* is calculated with reference to structural members and infill walls. Account is taken for the cost of all works related to repair (such as removal of rubble, replacement of plaster, etc.).

(iii) It is assumed that the cost of repair is proportional to the volume of the member. For structural elements cost is always referred to "critical regions", defined for convenience to extend half the member length; usually, though not necessarily both critical regions are repaired in the same way. The *total cost* of repair for a building is the sum of the repair costs of R/C critical regions and infill panels.

Damage and loss in R/C members

The model adopted for the correlation of structural damage and loss (cost of repair) for R/C members is shown in Fig. 1(a). Based on the limited data available in the literature (see Penelis & Kappos, 1996), it has been assumed that for rotational ductilities $\mu_\theta=\theta_{max}/\theta_y \geq 4$ the most costly repair technique is applied; typically, though not necessarily this technique involves *jacketing* of the R/C member (less costly techniques involve shotcreting, injection of resins, and gluing of metal plates). For $\mu_\theta < 0.75$ no repair is required, while the variation of repair cost from μ_θ=0.75 to 4.0 is assumed to be linear. The parameter D_c in Fig. 1 is the cost of repair (per critical region) normalised to the cost of the most expensive technique, hence maxD_c=1.

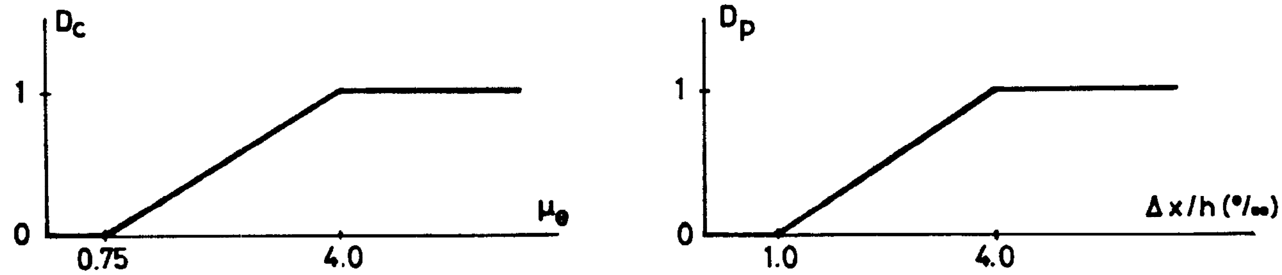

Fig. 1 Normalised economic damage indices for (a) R/C members; (b) Brick masonry infill walls.

A weighting factor w_i is defined for each critical region *i* as the ratio of concrete volume in the region to the total volume of all concrete members (beams, columns, walls). If the total number of R/C members is N, then

$\sum_{i=1}^{2N} w_i = 1$, since each critical region extends half a member length.

The economic damage index for the entire R/C structural system is

$$D_{cg} = \sum_{i=1}^{2N} w_i D_{ci} \tag{1}$$

and its max value D_{gc} = 1 corresponds to the case that all structural members are repaired using the most costly technique ($\mu_\theta \geq 4$ in all R/C members). If the total cost of these repairs is C_c and the total value of the building (including structural and non-structural elements, as well as all installations) is C_{tot}, then the economic *repair index* for the entire R/C structural system is defined as

$$G_c = D_{cg} \cdot \frac{C_c}{C_{tot}} \tag{2}$$

and expresses the cost of repair as a fraction of the total cost of the building. Bearing in mind that the value of an existing building, having an age T_n years, is not the same as that of a similar new building (for which C_{tot} can be readily evaluated from current market rates), the cost can be estimated as

$$C_{tot,n} = \left(\frac{T_{rem}}{T_d}\right)^{\gamma} C_{tot,0} \tag{3}$$

where T_d is the design life of the structure and $T_{rem}=T_d-T_n$ its "remaining" life after *n* years. Based on data from Greek practice, T_d=67 yrs and γ=1 may be assumed, corresponding to an annual depreciation of 1.5%.

Damage and loss in infill walls

A (structural damage) - (loss) correlation model similar to the one used for R/C members was assumed for infill wall panels, as shown in Fig. 1(b). Note however that loss is now correlated to the interstorey drift ratio, and that the repair techniques are different from those used for R/C members; in the case of infills the most costly repair consists in demolition of the existing panel and construction of a new one. The repair index for the infill panels is now defined as

$$G_p = D_{pg} \cdot \frac{C_p}{C_{tot}} \tag{4}$$

where the global economic damage index D_{pg} is defined similarly to D_{cg} in equation (1) and C_p is the total cost of replacing all the panels in the building.

Quantification of loss indices

A systematic analysis of data concerning repairs carried out in Thessaloniki after the 1978 earthquake (Penelis et al., 1988) has led to the following equations relating the individual damage indices D_c and D_p to the global repair indices G_c and G_p of equations (2) and (4); both equations refer to R/C buildings with dual structural systems (frames and walls), which is the most common type of R/C structure in Greece and elsewhere, designed to the seismic regulations applicable from 1959 to 1985 (when a new Code was introduced).

- Medium-rise structures (3-5 storeys): $G = G_c + G_p = 0.25D_c + 0.08D_m$
- High-rise structures (8-10 storeys): $G = G_c + G_p = 0.30D_c + 0.08D_m$

It is worth pointing out that if a building has suffered repairable damage, the required cost of repair does not exceed 38% of the value of a similar *new* building; it is obvious then that repair, rather than reconstruction should be the optimum solution for all structures with a remaining life of 25 or more years (see equation 3). The foregoing empirical relationships strictly apply to economic parameters (such as relative cost of materials and workmanship) pertinent in Greece; appropriate adjustments are obviously required in countries where these parameters are significantly different.

DAMAGE SCENARIO FOR THESSALONIKI

Complete scenarios of damage and loss have been developed for the city of Thessaloniki for two different hazard assumptions

- A 6.5 magnitude event identical to that of the 1978 earthquake
- A 7.0 magnitude event, which might be considered as the design earthquake for the area.

Site-specific acceleration time-histories have been developed for 10 characteristic locations in the city, using standard shear-beam analysis (see Kappos et al. 1991); in estimating these time-histories it was assumed (due to lack of pertinent data) that the motion at bedrock would have essentially the same frequency characteristics for the two events, the main difference laying in the peak ground acceleration.

The vulnerability of typical medium- and high-rise R/C buildings was estimated by analysing "generic" structures with bare and brick masonry-infilled frames and with R/C walls, taking due account of the inelastic characteristics of each member (Kappos et al. 1992). A total of six different structures was analysed, including buildings with open storeys (pilotis). For each structure ductility factors and interstorey drifts were calculated (for each member or storey) in each of the ten locations in the city, for either hazard scenario; a total of 120 (= 6·10·2) analyses were run.

Ductilities and interstorey drifts from the previous analyses were then introduced in the loss models described in the previous section and the required cost of repair was determined in each case. Due to space limitations only the final results will be discussed herein.

Summarised in the table are the costs of repair (as % of new building cost) calculated for bare, infilled and pilotis buildings for the two hazard scenarios (M=6.5 and 7.0); the values represent the *average* of the ten locations studied, hence site effects (which were quite important) cannot be inferred from this table.

	Medium-rise			High-rise		
M=6.5	Infills	R/C	Total	Infills	R/C	Total
Bare	1.28	1.85	3.13	3.52	4.31	7.83
Infilled	0.08	0.43	0.51	0.76	0.49	1.25
Pilotis	0.37	0.56	0.93	0.65	0.37	1.02
M=7.0						
Bare	2.05	3.35	5.4	3.62	5.39	9.01
Infilled	0.71	1.34	2.05	3.56	1.86	5.42
Pilotis	1.09	1.39	2.48	1.55	1.64	3.19

It is seen that, with the exception of bare frame buildings, damage in both medium-rise and high-rise buildings is minor for the 6.5 event. Bearing in mind that bare frames constituted just a small fraction of the building inventory (less than 5%), the estimated ratios are in good agreement with the values calculated for the 1978 earthquake (Penelis et al. 1988), for which the total cost of repairs amounted to approximately 1% the cost of (new) buildings. With regard now to the scenario for the future 7.0 earthquake, it is seen that damage will be quite higher; this is particularly true in the case of high-rise buildings where cost of repair to the (very common) infilled frame-wall systems will be approximately 4 times higher than in the 1978 earthquake. Such type of quantitative information is believed to be invaluable in designing earthquake mitigation strategies.

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