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Development of earthquake damage scenarios using a comprehensive analytical method

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ABSTRACT: A comprehensive methodology for the development of earthquake damage scenarios is suggested and applied in the case of the city of Thessaloniki. Based on the available seismological and geotechnical data, model accelerograms are specified for different locations in the city. The inelastic seismic response of various types of buildings subjected to these accelerograms is determined, using appropriate inelastic models for both R/C elements and masonry infill panels. Starting from data for cost of repair of the structures in the city, available from the 1978 earthquake, a correlation with the analytically derived seismic damage indices is established, using a simplified (damage index)-(cost of repair) model. This information serves as a basis for developing a damage scenario for the city.

1 INTRODUCTION

An important tool used for the assessment of urban seismic risk is the so called "damage scenario". Comprehensive studies, starting from the estimation of the maximum credible earthquake and concluding with the estimation of damage distribution in the structures of a certain area are quite rare. As a rule, such studies do not include information on the expected cost of damage (Seidel et al. 1989), or this cost is calculated using macroscopic information based on past experience (Thomas 1990), without detailed correlation with structural damage estimates made for each member of the structures studied.

Presented in this paper is a comprehensive methodology, including seismological, geotechnical and structural investigations, used to predict the response of the city of Thessaloniki (Macedonia, Greece), to the maximum earthquake expected in the area. Although developed for the specific case considered, the methodology is of somewhat broader interest, particularly in the common case of urban areas for which strong motion records are scarce, while statistical information concerning damage from previous earthquake is available. The paper focuses on the structural aspects of the procedure.

2 SUGGESTED METHODOLOGY

2.1 *Outline of procedure for developing the damage scenario*

The suggested methodology includes the following steps:

1. Based on the seismological data for the area under consideration, including any available strong motion records, the design earthquake is determined in the form of an accelerogram at bedrock. In the usual case that the existing records were obtained at a certain distance from bedrock, the design motion at bedrock has to be estimated, taking into account local soil characteristics, typically with the aid of "shear beam" analysis (Kappos et al. 1991).
2. Based on the geotechnical data (soil profiles) for various characteristic parts of the area under consideration, design accelerograms at surface ("free-field") are determined, using standard "shear beam" analysis.
3. Using these accelerograms as input, the response of a series of analytical models representing the buildings in the area, is determined. These models should properly take into account the hysteretic response characteristics of the members of typical structures in the area considered.
4. The critical response quantities calculated during the previous step are used to estimate damage potential, as well as the cost of repairing the structures, using appropriate models correlating structural damage indices, such as ductility factors and interstorey drift ratios, to an economic damage index, such as the cost of repair (per unit volume).
5. Assuming that the selected parts of the area studied are characteristic of the overall response, and relating the cost figures calculated in the previous step to the actual volumes of the building stock, an earthquake damage scenario can be developed, to which estimates of potential collapse (from step 4) should be included.

The reliability of the suggested method is increased whenever recorded accelerograms, as well as corresponding data for the cost of repair are available, in which case they are used to calibrate the models correlating structural and economic damage indices.

2.2 *Modelling of structures and damage*

An important consideration in the suggested methodology is the degree of sophistication warranted for the modelling of structures analysed in each selected part of the area under consideration (step 3). It is understood that the level of modelling should be compatible with the numerous uncertainties involved in all steps of the suggested procedure, and in addition considerations regarding the economy of analysis should be taken into account. It appears, therefore, that two possible approaches could be adopted in the following procedure.

1. Consideration of a large number of "macro-models", i.e. models with one or a few degrees of freedom, covering a wide spectrum of natural periods (the actual limits depend on the structural characteristics of the buildings in the area considered). Such models should necessarily depict the main structural features of the buildings, the most important one being the inelastic response, as determined by the yield level and the type of hysteresis (stiffness and strength degradation, reduced energy dissipation capacity and so on).

2. Consideration of a small number of "medium level" models, based on an element-by-element discretisation, and selected so as to represent the most common types of buildings in the area under consideration. Again the appropriate description of the inelastic response characteristics is the key to the success of the model, only that in this case the determination of the main parameters is somewhat more straightforward than in the case of macro-models. It has to be stressed out that all the elements of the structures under consideration contributing to its seismic capacity should be accounted for in the analytical model. Such elements that are usually neglected in structural modelling, although they contribute significantly to both the lateral stiffness and the strength of a building, are masonry infill panels used as partitions and/or exterior cladding in reinforced concrete structural systems.

The advantages of the first approach are the capability to consider the whole spectrum of natural periods, and, of course, the reduced cost of analysis. The advantage of the second approach is the more accurate description of the behaviour of actual structures, and also the possibility to correlate the calculated response parameters to the required cost of repair, as suggested in the following section. Ideally, the two approaches should be combined to render a clearer picture of the earthquake response of the building stock.

In the case-study presented in this paper the second approach to structural modelling was adopted. The analytical models of the buildings included linear elements with lumped plasticity used for R/C members (beams, columns and walls). The hysteretic behaviour of these elements was governed by the bilinear version of the Takeda model, as incorporated in the standard DRAIN-2D computer code. Plane elements (shear panels) were used for the modelling of brick masonry infills, which are the typical "non-structural" elements in Greece, as well as in many other countries. A refined hysteresis model was developed for these panels, including strength and stiffness degradation, as well as the pinching effect. This model was developed on the basis of experimental data regarding R/C frames infilled with brick masonry walls, tested at the University of Thessaloniki (Valiasis & Stylianidis 1989). The sceleton curve of the model is shown in Fig.1, while the various post-elastic hysteresis rules can be seen in Fig.7.

A number of standard structural damage parameters are calculated by the DRAIN-2D/90 program (an extended micro-computer version of the well known program) for each R/C element. A procedure for calculating corresponding damage indices based on a supply/ demand approach, both at local and at storey level, has also been recently proposed (Kappos 1991). Establishing a correlation between analytically calculated structural damage indicators and economic damage indicators, such as the cost of repair, is a key step in developing a damage scenario.

Based on the limited experimental data available from the literature, as well as to damage observations in real structures, the simple models of Fig.2 are proposed. For R/C elements the cost of repair is related to the rotational ductility requirement in each critical region, assuming average member dimensions (Fig.2(a),(b)). The step-wise diagram is established considering the different repairing techniques (grouting with epoxy resins, fixing of metal plates, jacketing), used in accordance with the severity of damage. A corresponding model for brick masonry infills is shown in Fig.2(c), whereby the required cost of repair is related to the interstorey drift ratio. Again the three steps correspond to different techniques, namely replastering, use of wire fabric, and demolition/reconstruction. In order to reduce the sensitivity of calculated cost figures, it was found more appropriate to use linear approximations to the step-wise diagrams, as shown in Fig.2.

3 APPLICATION TO THE CITY OF THESSALONIKI

3.1 *Seismological and geotechnical data*

On the basis of mainly historical data, it was estimated (Voidomatis 1986) that the most propable earthquake for the area where Thessaloniki lies has a magnitude $M_L=6.5$, with a probability of exceedance 84% in 40 years, while the maximum earthquake has a magnitude $M_L=7.0$, with a probability of exceedance 83% in 80 years. The corresponding maximum ground accelerations at bedrock in the city of Thessaloniki are 0.175g and 0.275g, respectively.

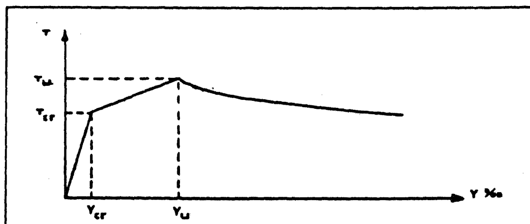

Fig.1. Sceleton curve for the infill wall hysteresis model.

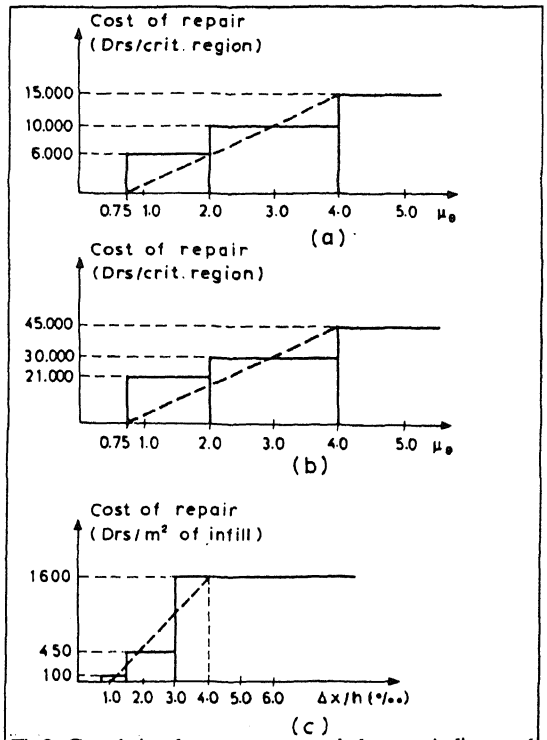

Fig.2. Correlation between structural damage indices and cost of repair : (a) R/C linear elements, (b) R/C walls, (c) Brick masonry infill panels.

The only available strong motion records were the four accelerograms obtained during the 20.6.78 earthquake and the aftershock of 5.7.78. Using the shear beam model, it was possible to estimate the bedrock motion from the surface motion recorded during the main shock and this was considered as the design motion for an earthquake with M_L=6.5. A similar motion, with a peak acceleration of 0.275g was calculated for the earthquake with M_L=7.0. It is understood that the conclusions of the present study may not be valid in the case of a future earthquake having a frequency content and a duration of strong motion substantially different from those of the 1978 earthquake.

Based on the geotechnical map of Thessaloniki as well as on the map of damage distribution during the 1978 earthquake, shown in Fig.3, ten characteristic locations were selected for the investigation, in such a way as to include the central and the eastern part of the city, for which statistical data concerning the required cost of repair were available (Penelis et al. 1988). Surface motions at these ten locations were estimated from the design motions at bedrock, using standard vertical shear.beam analysis and taking the mechanical and dynamic characteristics of the soil layers into account.

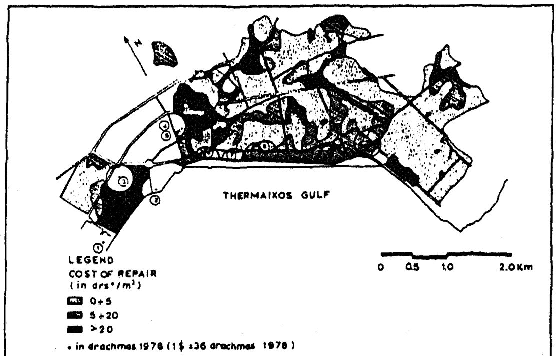

Fig.3. Distribution of damage during the 1978 earthquake and location of the ten areas selected for the present study.

3.2 *Structures analysed*

The most common type of structure in the area under consideration is the cast in situ reinforced concrete building. The structural system is in most cases a dual one, involving both frames and R/C walls. Brick masonry infill walls are typically used for exterior cladding and interior partitions. It has to be pointed out that the majority of the buildings in the city have a rather irregular configuration.

The following structures were selected for the study, taking into consideration the existing building stock, the limitations of the analytical tools available, and the cost of analysis:

1. A nine-storey building with a dual structural system consisting of R/C walls and frames, idealised as shown in Fig.4(a).
2. A similar four-storey building, idealised as shown in Fig.4(b).

Both buildings were designed to the 1954 and 1959 Greek regulations (applicable at the time of the 1978 earthquake), for a base shear equal to 6% their total weight, which is the seismic coefficient used in the majority of buildings in Thessaloniki. Although ignored at the stage of design (according to standard practice, even nowdays), masonry infills were taken into account in the dynamic time-history analysis. The standard case studied was the one with infills along the whole height of the exterior frame, but additional analyses with an open first storey ("pilotis" building) and without any infills were also carried out.

3.3 *Limitaions of the analytical procedure*

In addition to the limitations involved in estimating the input motions, the following main limitations of the methodology used to evaluate the seismic response of buildings should be pointed out:

1. Only plane structures are analysed, therefore factors such as torsion due to non-symmetric arrangement (in plan) of R/C and/or masonry walls, and biaxial behaviour of columns are neglected.
2. The modelling assumptions used in DRAIN-2D/90 are realistic in the case of R/C members with predominantly flexural behaviour, whereby premature failure due to shear and/or inadequate anchorage of steel bars is excluded. These

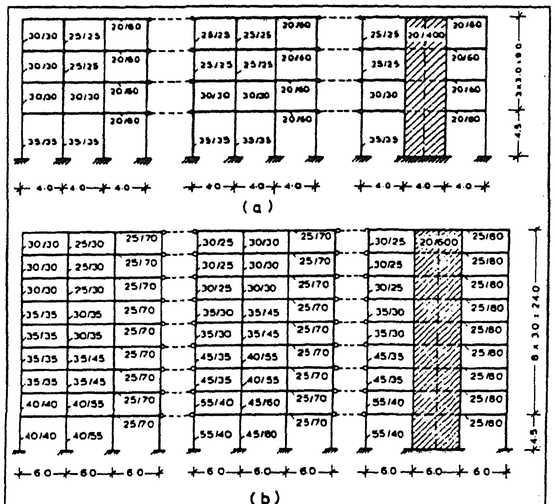

Fig.4. Analytical models of the structures analysed: (a) Four-storey building, (b) Nine-storey building.

conditions are hardly applicable in numerous actual buildings in Greece; serious problems of inadequate design and, in particular, of inadequate detailing often exist.

3. The statistical data regarding the cost of repair after the 1978 earthquake, to which analytically calculated figures are correlated, do not always constitute an objective representation of the damaged structure. Based on the personal experience of the authors, it is beleived that in some cases the cost of repair was considerably higher than that justified by the actual degree of damage,while in other cases,damages that should have been repaired were not repaired at all.

4. For reasons of economy of computation, only four- and nine-storey buildings with dual structural system were analysed. The results from these analyses were correlated to damage statistics concerning buildings with 3 to 5 and 7 to 9 storeys, respectively, to obtain a statistically reliable sample. In one of the locations (No.3) a substantial number of buildings without R/C walls was included in the statistical sample. It is understood that, quite often, the structures compared have substantially different characteristics.

5. Given the scarcity of related experimental data and the ambiguities involved in their interpretation, and also the fact that the selection of the required repairing technique is a rather subjective matter, the models for the correlation of structural damage indices and corresponding cost of repair(Fig.2) should be considered simply as a first rational approach to the problem.

3.4 *Discussion of the results*

Shown in Fig.5 and 6 are the distributions of interstorey drift ratios and member ductility factors along the height of the structures analysed. Two curves are indicated in each diagram, one corresponding to the location where the maximum cost of repair (per unit volume) was calculated and the other to the minimum one. As a rule, these are also the locations, where maximum and minimum structural damage indices (Δx, μ_θ) were calculated, while the response in the other locations lies within the two limits shown in the figures.

It is clearly seen in the figures that the response of both structures varies substantially with each motion, a fact that points out to the importance of considering the influence of local soil conditions on the bedrock motion, which was assumed to be the same for all locations. It is also of interest that the critical location is not the same for both the four- and the nine-storey structure. This, of course, is a consequence of the different frequency content of the motion at each location.

The values of the various structural damage indices are quite moderate, especially in the case of the four-storey structure. Interstorey drifts do not exceed 0.1% in the four-storey structure and are just above 0.2%(in the most critical case) in the nine-storey structure. Corresponding maximum member ductilities range from about 2 in the four-storey structure to about 5 in the beams of the nine-storey structure. It is believed that the main reason for the more favorable behaviour of the four-storey structures, which can not be attributed to higher spectral values is the substantially higher level of overstrength available in the four-storey structure, resulting from both minimum code requirements (for member dimensions and reinforcement) and from the increased contribution of the masonry infills (which have the same thickness and the same shear strength in both buildings) in the sei smic capacity of the building.

Checking of the ratio of required to available ductility in R/C members, according to the procedure suggested by Kappos(1991), indicated that this ratio is well below unity in all cases. It was, therefore, concluded that for the M_L=6.5 earthquake, no collapse should be expected in R/C buildings with reasonably symmetric arrangement of the lateral force resisting elements, fully conforming to the 1954/1959 Regulations. It is understood that this conclusion can not be straightforwardly extended to other types of buildings. Indeed,during the 1978 earthquake, the only collapse of R/C structure involved a building of highly irregular configuration and with poor detailing of structural members.

Using the models of Fig.2, the required cost of repair for the two structures analysed was estimated. Scaling the calculated costs per unit volume according to the actual volume of the building stock in each location (included in the sample were buildings within the 400m diameter circles indicated in Fig.3), the required total cost per location was estimated. These values should match the corresponding ones calculated for the repair of the 1978 earthquake damage in a previous study (Penelis et al.1988). The correlation between the two sets of data is shown in Fig.8, for nine of the ten locations studied, since no statistical data were available for location 1. It is seen that, with the exception of locations 7 and 9, the correlation is quite good (coefficient of correlation r=87.5%). Indeed, if these two locations are excluded, the correlation is exceptionally good (r=99%). It has to be mentioned here that in the

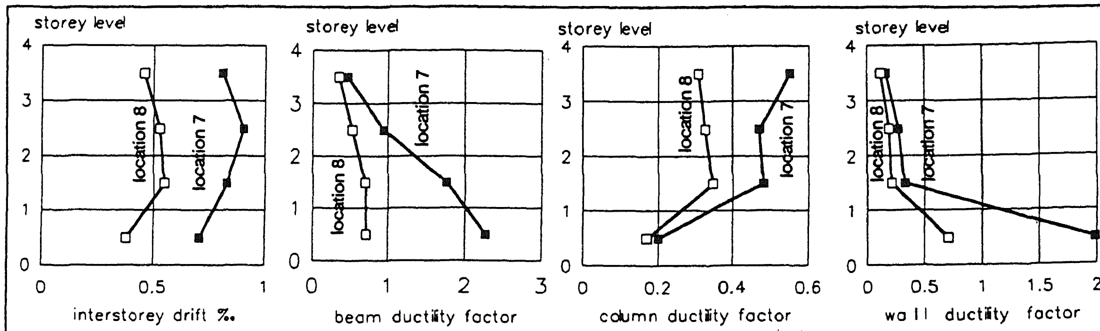

Fig.5. Distribution of main structural damage indices along the height of the four-storey structure (numbers in circles indicate locations as shown in Fig. 2).

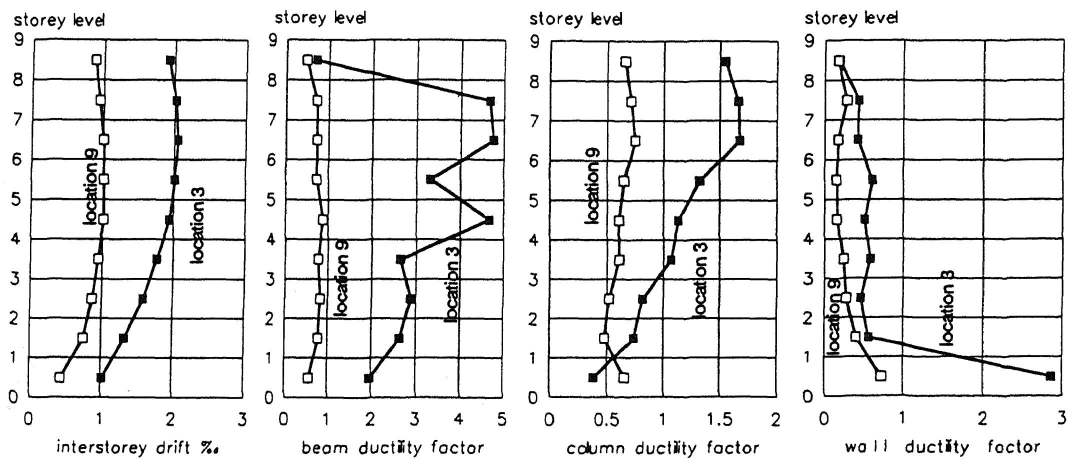

Fig.6 Distribution of main structural damage indices along the height of the nine-storey structure (numbers in circles indicate locations as shown in Fig. 2).

two locations where the correlation was poor, there was also a significant discrepancy between the spectral values of the input motions in the regions of the natural periods of the buildings under consideration and the corresponding available statistical data of the cost of repair.

Given the significant uncertainties involved in this complicated procedure (see section 3.3), comparisons between calculated and "actual" values should be made with reference to the largest size of sample possible. In this sense, perhaps the most meaningful comparison is that of the total cost of repair for all the locations studied. This figure amounts to 89.3mil. drs.(1978) in the statistical data, and to 73.4 mil.drs., i.e. 18% lower, in the analytically calculated data. It is believed that this is a very reasonable match, especially since no attempt was made to adjust the values in the models of Fig.2, and also no allowance was made for damage to members of the buildings studied not included in the analytical models of Fig.4 (that is beams and walls in the direction perpendicular to the one considered). If such an allowance were made, the two values of total cost would be even closer. Finally, it is interesting to notice that in a previous investigation (Kappos et al.1991), where infill panels were ignored in the analytical model, the calculated total cost for the same locations was 221.1mil.drs., which is 2.5 times higher than the actual one!

Some interesting results were obtained in the additional analyses concerning buildings without masonry infills in the first storey or in all storeys (bare R/C structural system).For instance, in the most critical location (No.3) for the nine-storey building the analysis of the structure with an "open" ground storey (pilotis building) indicated that the required cost of repair for the R/C elements was only half that for the building with infills in all storeys, while the cost for the masonry panels was 37% lower. This somewhat surprising result (pilotis buildings are known to be more vulnerable than the ones with "closed" ground storeys) can be explained on the basis of localisation of damage in the lower part of the building, in particular at the ground storey. For a moderate excitation such as the one considered, apparent economies in cost of repair result from such a localisation, but for a stronger motion collapse of the ground storey may occur and the whole building has to be demolished and reconstructed. With regard to the building without any infills, it was found that the required cost of repair for the R/C elements was slightly (8%) lower than that for the building with infills, which should be attributed to

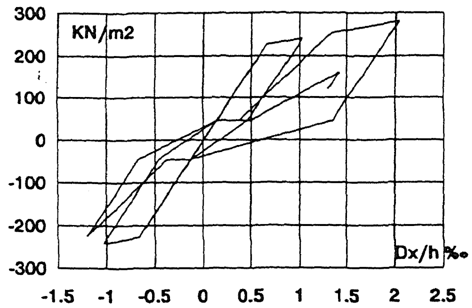

Fig.7. Hysteresis curve for masonry infill panel in location 3 (7th storey of nine-storey building).

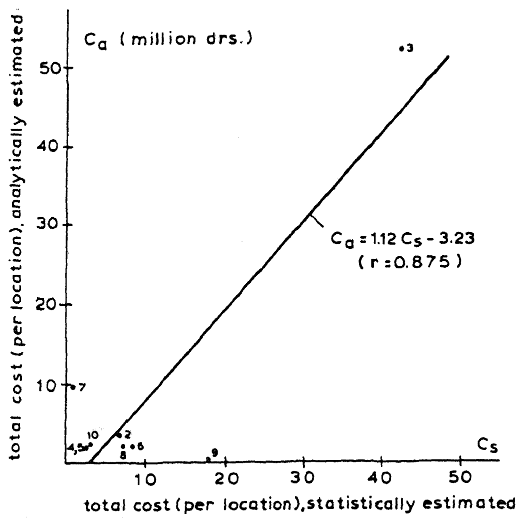

Fig.8. Correlation between analytically and statistically obtained values of total cost of repair for the 1978 earthquake.

the fact that the period of the bare frame (T=0.94sec) is 40% higher than that of the infilled structure (T=0.67sec) and the corresponding spectral values are lower.

Based on the information briefly presented above, a complete damage scenario can be developed for the city under consideration, when it is struck by the maximum earthquake (M_L=7.0). The actual cost of repair required in a particular location $C_a(7.0)$ can be estimated from the relation

$$C_a(7.0) = C_a(6.5)\,[C_c(7.0)/C_c(6.5)]$$

where C_c indicates calculated cost according to the procedure suggested herein. Assuming that the selected sample of buildings is representative of the city as a whole, the required cost of repair in any location can be estimated from the least squares equation of Fig.8.

4. CONCLUSIONS

The results of the present study indicate the potential advantages of the suggested methodology over traditional seismic risk studies leading to a prediction of the distribution of ground accelerations in an urban area. The proposed models correlating structural damage indices to required cost of repair can offer invaluable information regarding the extend of damage in a future earthquake.

Given the numerous and significant uncertainties involved in the problem studied, the correlation found between the calculated cost of repair for the city of Thessaloniki and the corresponding statistical data from the 1978 earthquake is quite promising, although significant discrepancies exist in some of the locations studied. The present research has also indicated that the distribution of damage within the city is far from being uniform, which points to a possible adjustment of the values of design base shear coefficients in each part of the city and for each structural system, rather than using a uniform value. This study has also confirmed the paramount importance of the presence of brick masonry infills in R/C structural systems. As a rule, such infills contribute significantly to both the strength and the stiffness of the buildings and lead to an overall improvement of their seismic behaviour. These remarks were also confirmed by the damage distribution in actual buildings during the 1978 earthquake.

The research programme presented herein is currently being completed at the Laboratory of Concrete Structures, Univ. of Thessaloniki, and results concerning the details of the damage scenario for the maximum credible earthquake (M_L=7.0) will be presented in the near future.

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