# TYPES AND CAUSES OF EQ INDUCED STRUCTURAL DAMAGE IN R.C. BUILDINGS IN GREECE

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SUMMARY

Types and causes of EQ induced structural damage in R.C. buildings in Greece are presented and classified. Damage cases are classified according to failure mode, limit state and frequency. Causes of damage are separated into causes of overstress and causes of understrength. The importance of causes of overstress and the need for further research is stressed.

## 1. Introduction

Rational presentation of structural damage surveys should include : (a) Mean load intensity, (b) Mean material and structural properties, (c) Detailed definition and frequency of each type of damage, (d) Analyses of the behavior of damaged structures, (e) Possible causes, degree and frequency of local overstress, and (f) Possible causes, degree and frequency of local understrength.

Separation of causes of damage into causes of local overstress and causes of local understrength is needed, so that the adequacy of the partial safety coefficients used in analysis and design {2,3} could be checked.

In the case of EQ induced structural damage in a large number of structures, such a rational presentation, although needed, is extremely difficult to be carried out. Thus, the effort should at least be concentrated towards obtaining objective judgements on as sound grounds as possible. Subsequently, sound engineering assumptions concerning behaviour of different materials and systems in EQ environment should be made and tested by detailed analytical and experimental procedures.

In what follows, an effort will be made to present and classify cumulative data on EQ induced structural damage of R.C. building structures in Greece, due to recent EQs.

## 2. Mean load intensity and material and structural properties

More than 500 cases of damage were examined.

The structures under examination were exposed to EQ induced ground motion, with an estimated intensity of VI ÷ VIII degrees of the MSK scale.

Only poured-in-place conventionally reinforced concrete buildings of the Moment Resistant R.C. frame type, with hollow-brick unreinforced infill masonry are examined. Most of the buildings, have also a number of R.C. shear walls with 2‰ reinforcement. For multistory residential buildings, at least one shear wall surrounds the main staircase.

Most of the structures are less than 25 years old, designed according to Greek 1959 Seismic Code, for a seismic coefficient of 0,04 ÷ 0,08, without specific reinforcement detailing specifications. Construction supervision by registered engineer is estimated to have been : (a) Continuous in 20% of the cases, (b) Scarce in 40% of the cases, (c) Negligible in 40% of the cases.

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Concrete quality ranges usually between C 8 ÷ C 16 {3}. In structures of less that 10 years old, steel S 400 is used rather extensively as main reinforcement, but stirrups are usually of S 220. In older structures S 220 prevails.

3. Definition and frequency of damage

A 75% of the exposed structures suffered damage, ranging from the on-set of serviceability limit state, to total collapse.

Only one total collapse of engineered R.C. structure was observed.

Detailed definition and frequency for all types of damage is impossible, due to missing statistical data.

Rough description and estimate of relative frequency for different types of damage is given in table 1.

Table 1. Types, degree and ralative frequency of damage

| Structural elements | Type of failure | Damage degree and frequency | |
|---|---|---|---|
| | | S.L.S. | U.L.S. |
| Beams | M<br>V | l<br>l | l<br>n |
| Columns | N<br>N + V | n<br>m | n<br>l - m |
| Short brackets | | l | n |
| Deep beams | | n | n |
| Beam - Column Joints | | l - m | l |
| Slabs | M<br>Diaphragm<br>Punching shear | n<br>n<br>l | n<br>n<br>n |
| Shear walls | V<br>Lateral buckling | l<br>n | n<br>n |
| Infill masonry | Separation<br>Tensile cracking<br>Compr. crushing<br>Dissintegration | h<br>m - h<br>-<br>- | -<br>l - m<br>l<br>l - m |
| Foundations | Structural<br>Soil | n<br>n | n<br>n |

Remarks
S.L.S.: Serviceability Limit State
U.L.S.: Ultimate Limit State
- : Non applicable
n : Negligible frequency ( 0 ÷ 20%)
l : Low frequency (20 ÷ 40%)
m : Medium frequency (40 ÷ 70%)
h : High frequency (70 ÷ 100%)

M : Bending moment
N : Axial load
V : Shear

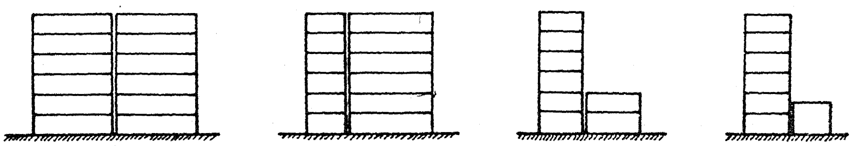
The most frequent types of damage were : (a) Separation between infill masonry and surrounding R.C. elements, (b) Tensile cracking of infill masonry, and (c) Column damage due to combination of N+V.

The first two prevailing types of damage, although of the S.L.S. level, proved to be of great economic importance.

## 4. Possible causes and degree of local overstress

Close examination of structures with moderate to severe damage, indicated the possibility of the following causes of local overstress : (a) Structure to structure interaction, (b) Morphology problems, and (c) Frame to infill interaction.

Structure to structure interaction happened when two separate structures are in contact with one another, but w/o a seismic joint. Interaction became more severe as difference in lateral stiffness, in total height and in storeys height increased

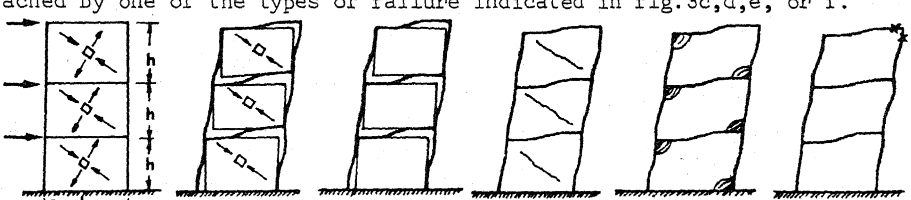


(a) Equal stiffness. Equal storey heights
(b) Different stiffness. Equal storey heights
(c) Different height. Equal storey heights
(d) Different height. Unequal storey heights

Fig.1 Structure to structure interaction

Morphology problems were also proved to be a major cause of local overstress. Morphology problems can be divided (fig.2) into {6}: (a) Building morphology problems, (b) Structural element morphology problems, and (c) Structural system morphology problems.

For low load intensity, the infilled R.C. frame behaved as a composite shear wall, working in the "uncracked" mode (fig.3a). When the load (or imposed deformation) reached a certain level, the limit state of separation was reached and, for further increase of loading, the composite structure entered the cracked mode (fig.3b). The ultimate failure was reached by one of the types of failure indicated in fig.3c,d,e, or f.




(a) Uncracked mode
(b) Cracked mode
(c) Separation (S.L.S.)
(d) Tensile cracking (S.L.S. or U.L.S.)
(e) Compression crushing (U.L.S.)
(f) R.C members damage (U.L.S.)

Fig.3 Behaviour Modes and Limit States of a Moment Resistant Infilled Frame (MRIF)

## 5. Possible causes and degree of local understrength

A great number of causes of local understrength has been observed, the most important of them being : (a) Material understrength, (b) Poor

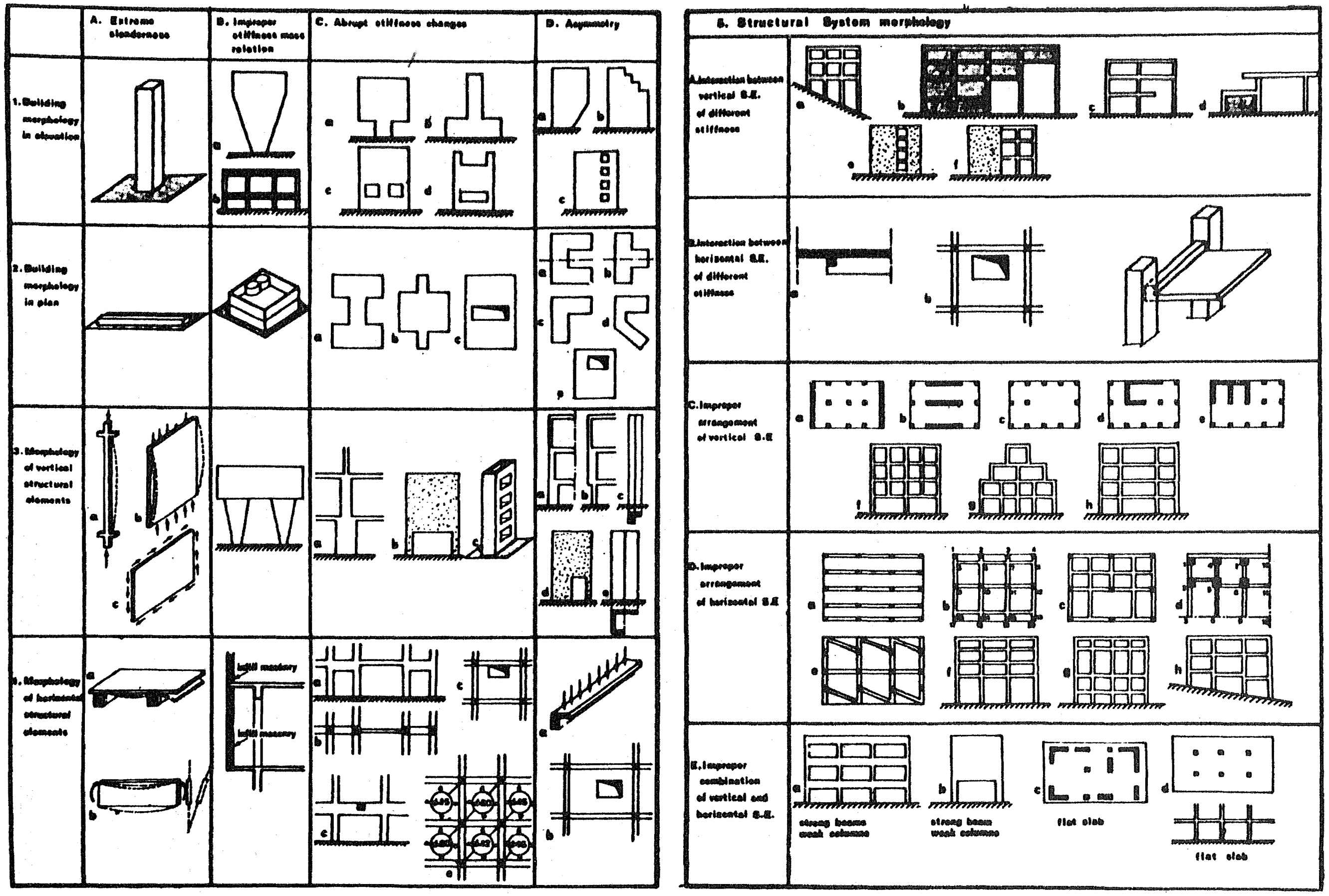



Fig.2 Building morphology problems

construction joints, (c) Abrupt reinforcement cutting - off, (d) Poor reinforcement joints, (e) Inadequate reinforcement anchorage, (f) Unauthorized interventions in the structural system, and (g) Improper design.

## 6. Examples of structural damage and conclusions

A number of typical structural damage cases is presented in pictures 1 ÷ 5, together with some brief comments.

In most of the cases, a combination of causes leading to overstress and understrength were responsible for the observed damage. Causes of overstress and causes of understrength are estimated to have been of approximately the same importance.

In a recent survey of damage cases in R.C. structures in Greece, in which cases of damage induced by EQ and fire actions were excluded {8}, it was found out that in approximately 80% of the cases the main cause of damage was a cause of understrength.

It is concluded, that causes of overstress (such as interaction and morphology problems) are more important in the case of EQ actions, than in the case of normal loading, and they should be given more attention.

## References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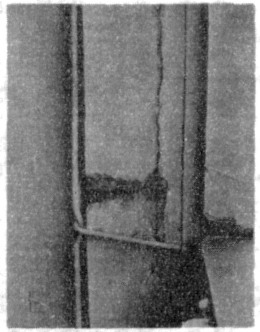
(a) Case A. General view

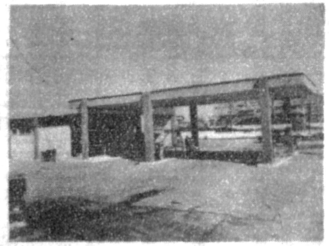


(b) Case A. Detail of column damage from inside

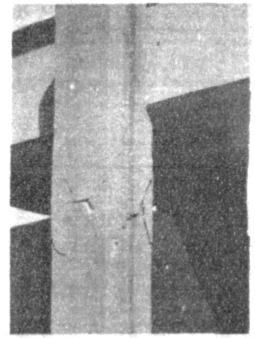
(c) Case B. General view and sketch of damage in main shear wall

(d) Detail of main shear wall damage (punshing)

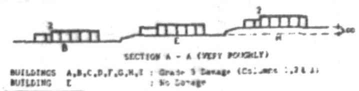
**P.1 Structure to structure interaction. Buildings with different total height and unequal storey heights. Compare with fig.1d.**

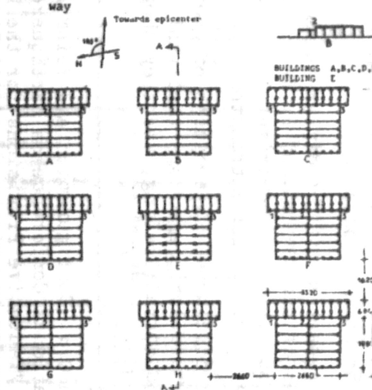


(a) Case C. General view of the structure. Compare with fig.2.5Ad.Four identical structures in different parts of the city were damaged in exactly the same way

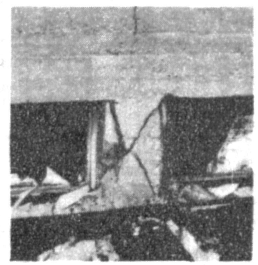


(b) Case C. Detail of short column damage



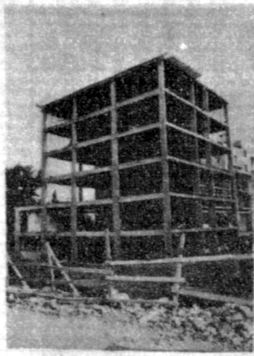

PLAN VIEW OF BUILDING GROUP



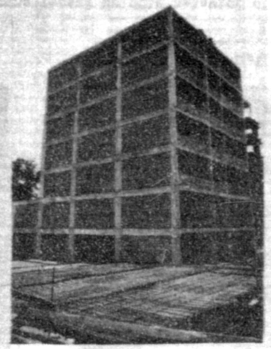
Detail of column damage

(c) Case D. Group of 9 buildings. Buildings A,B,C,D,F,G,H,I similar to fig.2.5Ad. Building E with slightly different configuration does not lead to slab displacement incompatibility

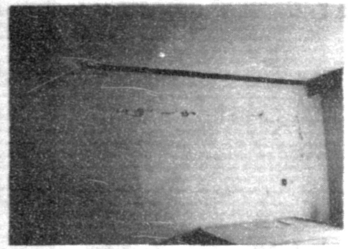
**P.2 Interaction between vertical structural elements of different stiffness (See also fig.2.5Ad)**



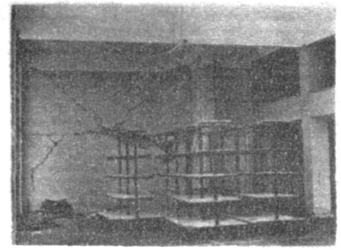
(a) Bare R.C. moment resistant frame (as designed)



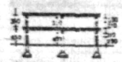
(b) R.C. moment resistant frame with hollow brick unreinforced infill masonry, before plastering



(c) Case E. R.C.-Infill separation (see fig. 4a)

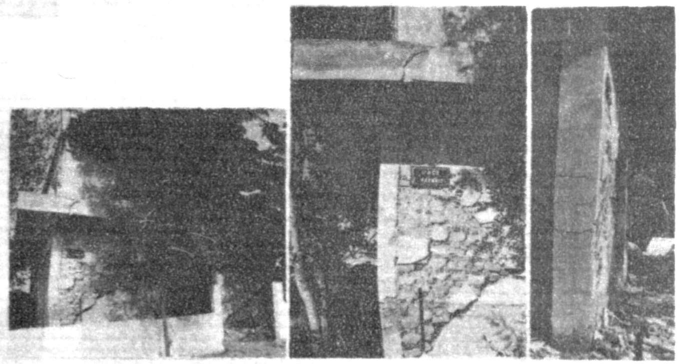


(d) Case F. Typical diagonal tensile cracking of the infill (see fig.4c)



(e) Case G. Two storey factory building. Free interior columns. Perimetrical columns act with a short free height, due to masonry infill. Compare also with fig.2.5Ad

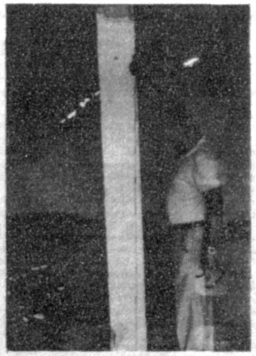
(f) Case G. Two storey factory building. All perimetrical columns were severely damaged, except corner ones, which were free to sway



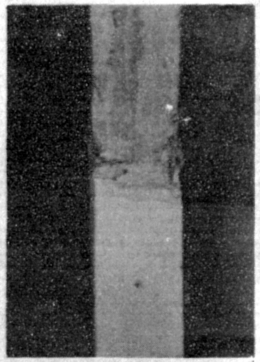
(g) Case H. Unexpected midheight column loading due to severe damage of poor quality hollow brick unreinforced infill masonry. Midheight column plastic hinge development. Adequate ductility of columns prevented total collapse

F.3 Interaction of R.C. moment resistant frame and hollow brick unreinforced infill masonry (See also fig.3 and 4)

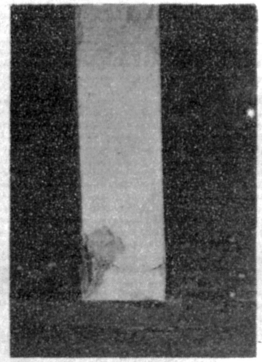
(a) Central column with plastic hinges at ends.. Drift 8 cm. Medium quality of construction. Not designed for EQ.



(b) Angular displacement of column axis

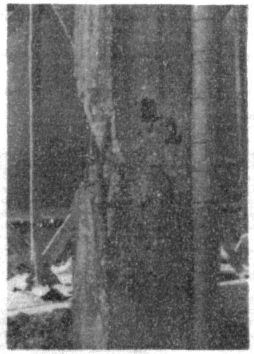


(c) Lower column end plastic hinge

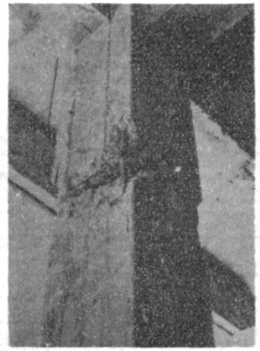


(d) Upper column end plastic hinge

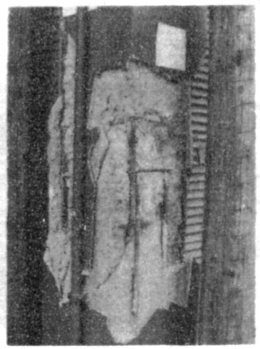
P.4 Ductile behavior of R.C. columns versus brittle behavior of hollowbrick unreinforced masonry (interior of structure of p.3g.Case H).



(a) Case I. Abrupt cutting-off of collumn reinforcement, together with weak and badly anchored stirrups (12 collumns of the same building were damaged in exactly the same way)



(b) Casé I. Poor construction joint, not reinforced properly (12 colummns of the same building were damaged in exactly the same way)



(c) Case J. Poor reinforcement joint. Lack of stirrups, small concrete cover and inadequate overlapping

(d) Case K. Inadequate anchorage of beam reinforcement in exterior frame joint, together with no confinement of joint

P.5 Structural understrength of linear elements