SEISMIC BEHAVIOUR AND DESIGN OF NON-SYMMETRIC BUILDINGS

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SUMMARY

This paper investigates possible improvements of the seismic response of non-symmetric reinforced concrete residential buildings, either by shear walls or bracings inserted into an existing structure, or by appropriate modifications of the original design.

INTRODUCTION

A correct seismic upgrading of a building, rather than strengthening all its members, requires the analysis of its response to a seismic input and the elimination of the most dangerous aspects, among which the torsional motions play a most prominent role.

This approach has been followed in a previous paper (Ref. 1) and in the present study, in which two reinforced concrete residential buildings are examined in order to investigate possible ways to eliminate torsional components from their principal modes of oscillation and maintain the stresses under standard seismic actions within admissible limits. Because of strict length limits set for this paper, details of buildings and calculations are given elsewhere (Ref. 2, Ref. 3).

FIRST BUILDING

The first building examined is a reinforced-concrete 4-storey residential building of Solofra (Avellino), which was diffusedly but not heavily damaged by the Southern Italy earthquake of 23 November 1980, which in Solofra reached MM 8 intensity (Ref. 1; Ref. 2).

The C-shaped plan of the building (Fig. 1) more than justified the damage. In Ref. 1 the introduction of bracings such to eliminate torsional components of free motion was studied. Three types of bracings were taken into consideration, as shown in Fig. 2.

The dynamic analysis of the building, with and without bracings, was performed by means of the well known TABS-77 computer program, run on the Honeywell DPS7 of the Computing Center of the University of Florence. Investigating by trial-and-error among bracing plans subject to architectural constrains related to the use of the building, the bracings shown in the first row of Fig. 3 were obtained as solutions of the set problem.

In the study just summarized, the building was assumed to be founded on a rigid soil. However, it is well known that the distribution of horizontal forces in braced buildings in very sensitive to soil compliance: it was therefore decided to investigate this aspect, limiting for simplicity the analysis to a Winkler sub-soil. Fig. 4 compares the percent decrease of bending moments caused by horizontal static forces in the columns of four structural frames when bracing of type (A) or (B) are introduced with the

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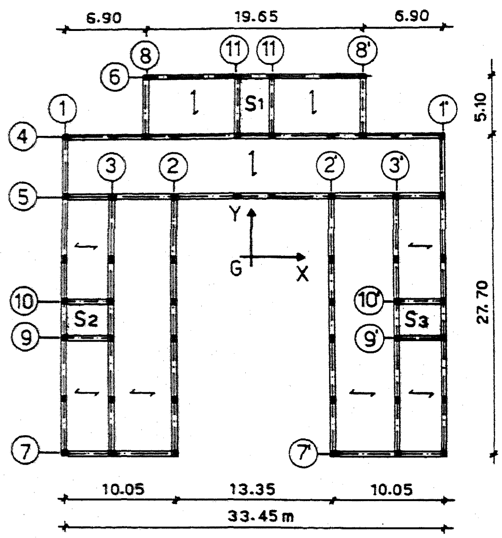
respective plan of the first row of Fig. 3, and the building is founded on a Winkler soil with compliance coefficient K=5 $kg.cm^{-3}$ or K=15 $kg.cm^{-3}$, or on a rigid soil (K= ∞): in the last case the diagrams coincide with the analogous ones presented in Ref.1. Inspection of Fig. 4 immediately shows that the stress relief in the columns is greatly reduced by the soil compliance, and in some cases (see especially Frame No. 7) the column moments are increased rather than decreased. In other words, the bracings designed for rigid foundation soil are not efficient on a deformable soil.

A convenient plan for each of the three types of bracings has been searched, assuming K=10 $kg.cm^{-3}$ and following the same procedure as in the case of rigid soil. The plans shown in the second row of Fig. 3 eliminate torsional components from the first two modes of oscillation in this case (Ref. 2). Fig. 5 refers to these bracing plans and compares the reductions in bending moments in the columns at each storey. In particular, Fig. 5-0 compares the three bracing types, while the other diagrams (Fig. 5-A, 5-B, 5-C) investigate, for each bracing type, the sensitivity to variations in the value of K, which is generally low, at least in the range 5-15 kg. cm^{-3}.



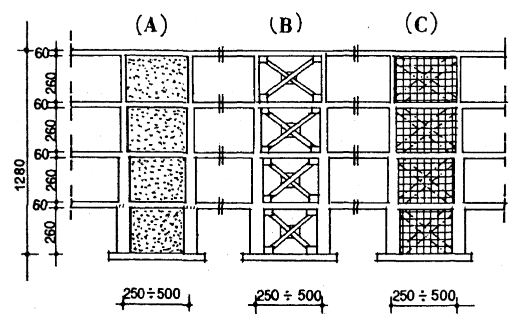


Fig.2: Bracing types investigated:
(A) r.c. shear walls;
(B) steel X-bracings;
(C) reinforced brick walls.

Fig.1: First case study: plan and structural frames.

SECOND BUILDING

The second case study (Ref. 3) refers to a 6-storey r.c. residential building in the city of Arezzo, 80 Km. south-east of Florence. No seismic provisions were included in its design, because only in 1982 Arezzo was included in the 2.d category (S=9) seismic zone: in particular, following a frequent practice in Italy, the frame beams are as deep as the floors (22 cm structural section depth). The dynamic behaviour of this building has been investigated by a specially developed computer programme (Ref. 4), which is

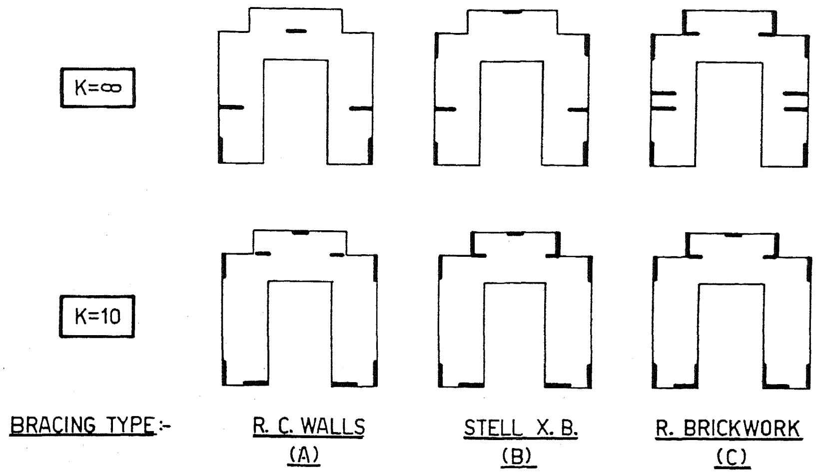


Fig.3: Bracing plans eliminating torsional components of free motion in case of rigid and deformable subsoil.

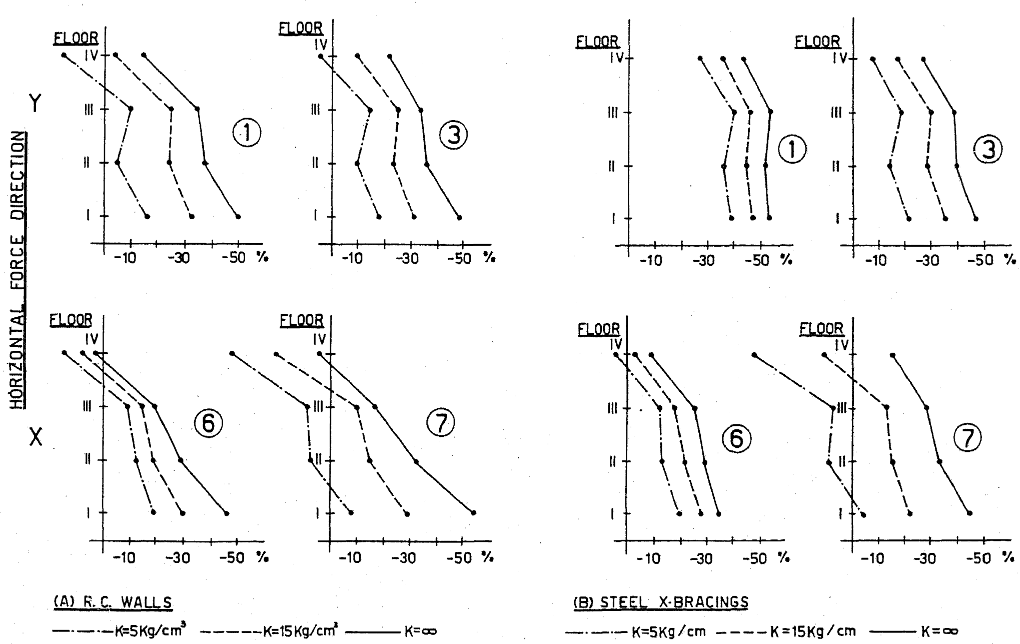


Fig.4: Percent reduction of sum of column bending moments in frames 1, 3, 6, 7 (cf.Fig.1) due to bracings with the plans of row K= ∞ in Fig.3. Comparison of the cases of rigid and deformable subsoil.

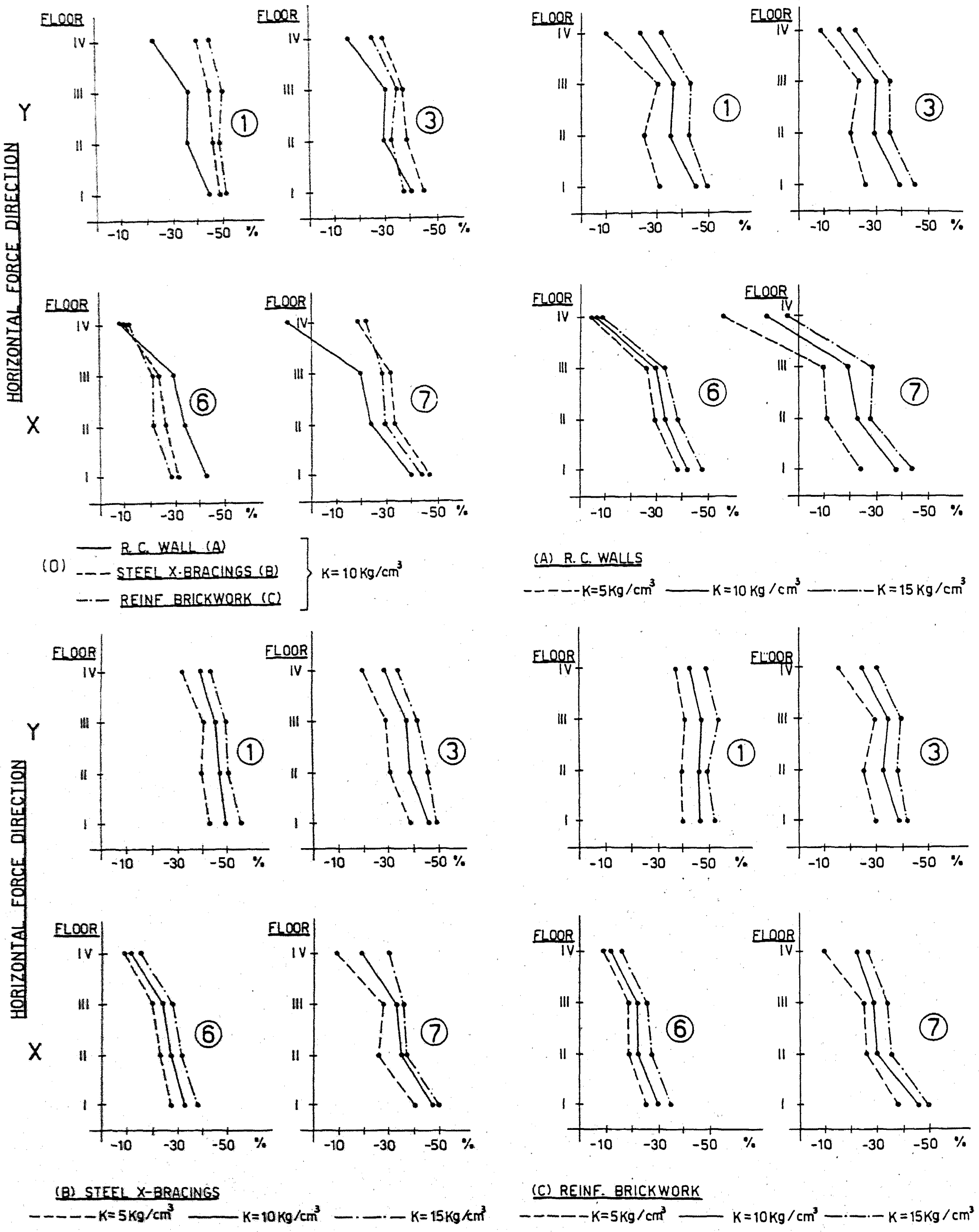


Fig.5: Percent reduction of sum of column bending moments in frames 1, 3, 6, 7 due to bracings with the plans of row K= 10 in Fig.3.
(O) Comparison of effects of different bracing types;
(A)(B)(C) Comparison of three soil compliances.

more suited than TABS for small computers and, moreover, takes account of torsional and warping stiffness of vertical members; calculations have been performed on the HP-1000 computer of the Department of Civil Engineering. Rigid restraints were assumed at the bottom of the columns, while a deformability equivalent to a soil compliance coefficient $K=10\ kg.cm^{-3}$ was assumed for the stair walls and the box and slab elements.

Note that the layout of this building (Fig. 6) appears much better than the previous one from the viewpoint of seismic response: nevertheless, due to the elongated shape and the eccentric staircase, very significant torsional components are present in the first two modes of oscillation (Fig.7-0).

The generally low stiffnesses caused a rather high fundamental period (T_1=1.23 sec), however below the limit for compulsory dynamic analysis set by the Italian Seismic Regulations (T_1=1.40 sec): but the inadequacy of static analysis for this building has been exhaustively proved in Ref. 3.

In this case, rather than studying the retrofitting of the existing building, it has been investigated which modifications could have been introduced in the original design, without altering the architectural layout, in order to improve its seismic response and in particular to eliminate torsional components from the first two modes of oscillation, and at the same time to keep the stresses below admissible limits when the building is subjected to the horizontal static forces prescribed for the S=9 Italian seismic zone (0.07 times the gravity loads). To this aim, the original design was modified in the following ways, as diagrammatically indicated in Fig. 7 (1 to 5):

TRIAL No.1: a) Transverse floor-incorporated beams, framing into the columns, added to the original structure; b) end columns displaced to the outside wall plane; c) increase to 30 cm of the depth of the beam all around the building perimeter;

TRIAL No.2: a), b), c) as above; d) section of the central end columns increased from 30x40 (or 30x30) cm to 30x100 cm;

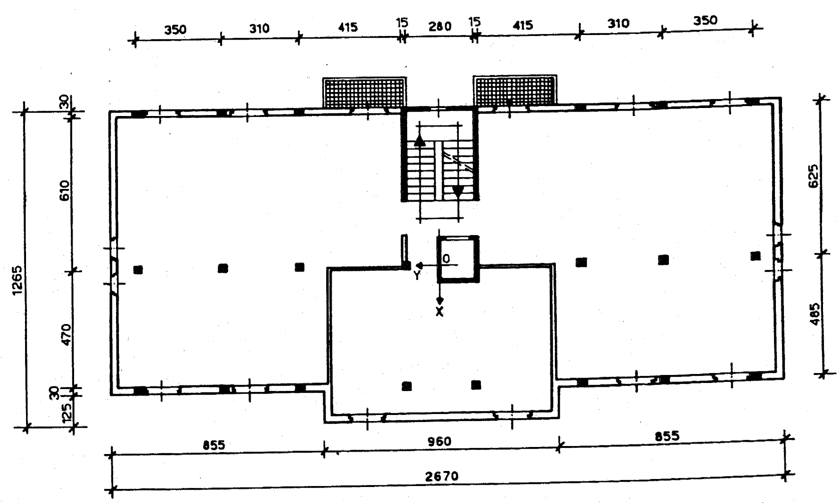
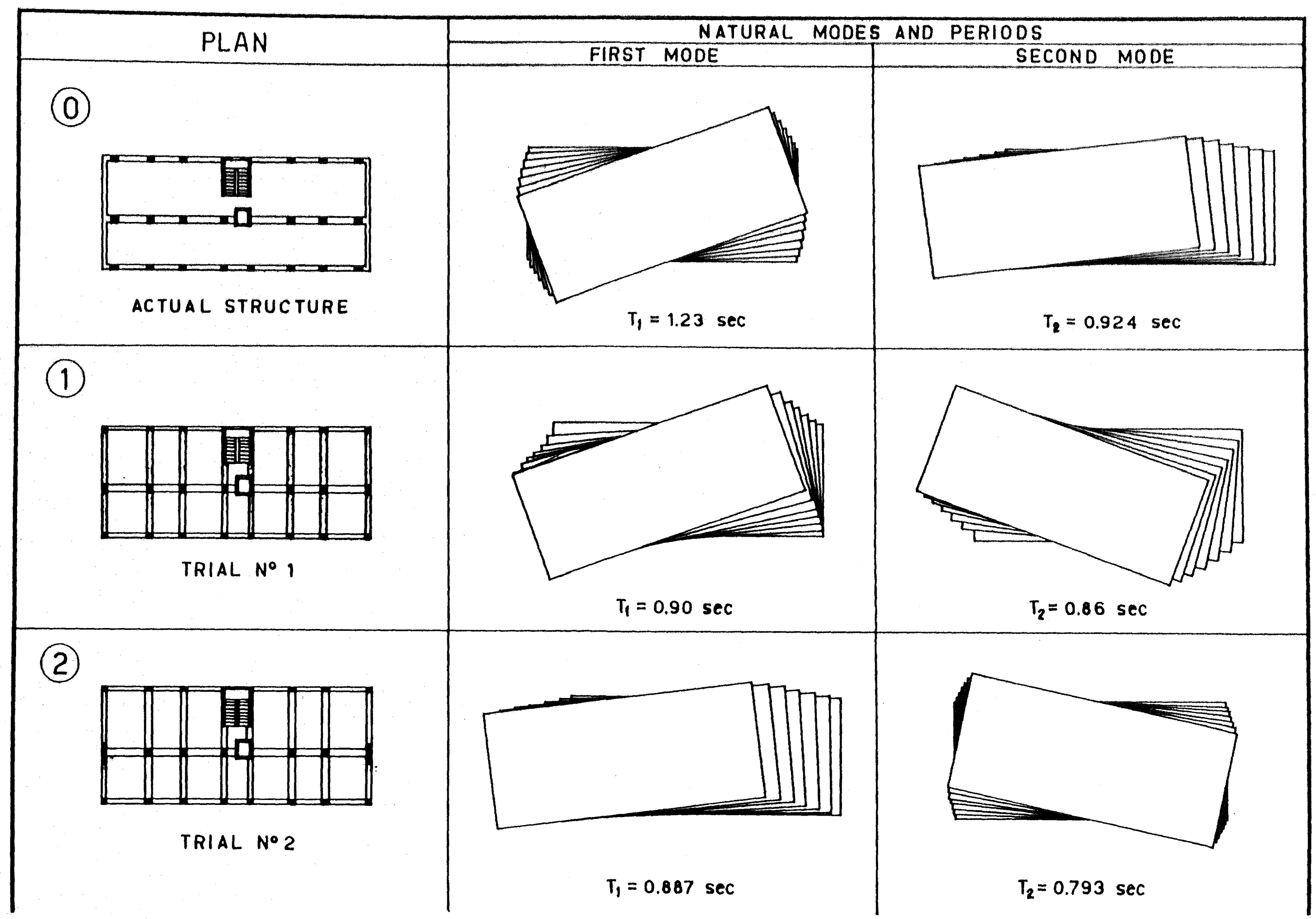


Fig.6: Second case study: overall plan and column layout.



PLAN
NATURAL MODES AND PERIODS
FIRST MODE
SECOND MODE
0
ACTUAL STRUCTURE
T_1 = 1.23 sec
T_2 = 0.924 sec
1
TRIAL N° 1
T_1 = 0.90 sec
T_2 = 0.86 sec
2
TRIAL N° 2
T_1 = 0.887 sec
T_2 = 0.793 sec

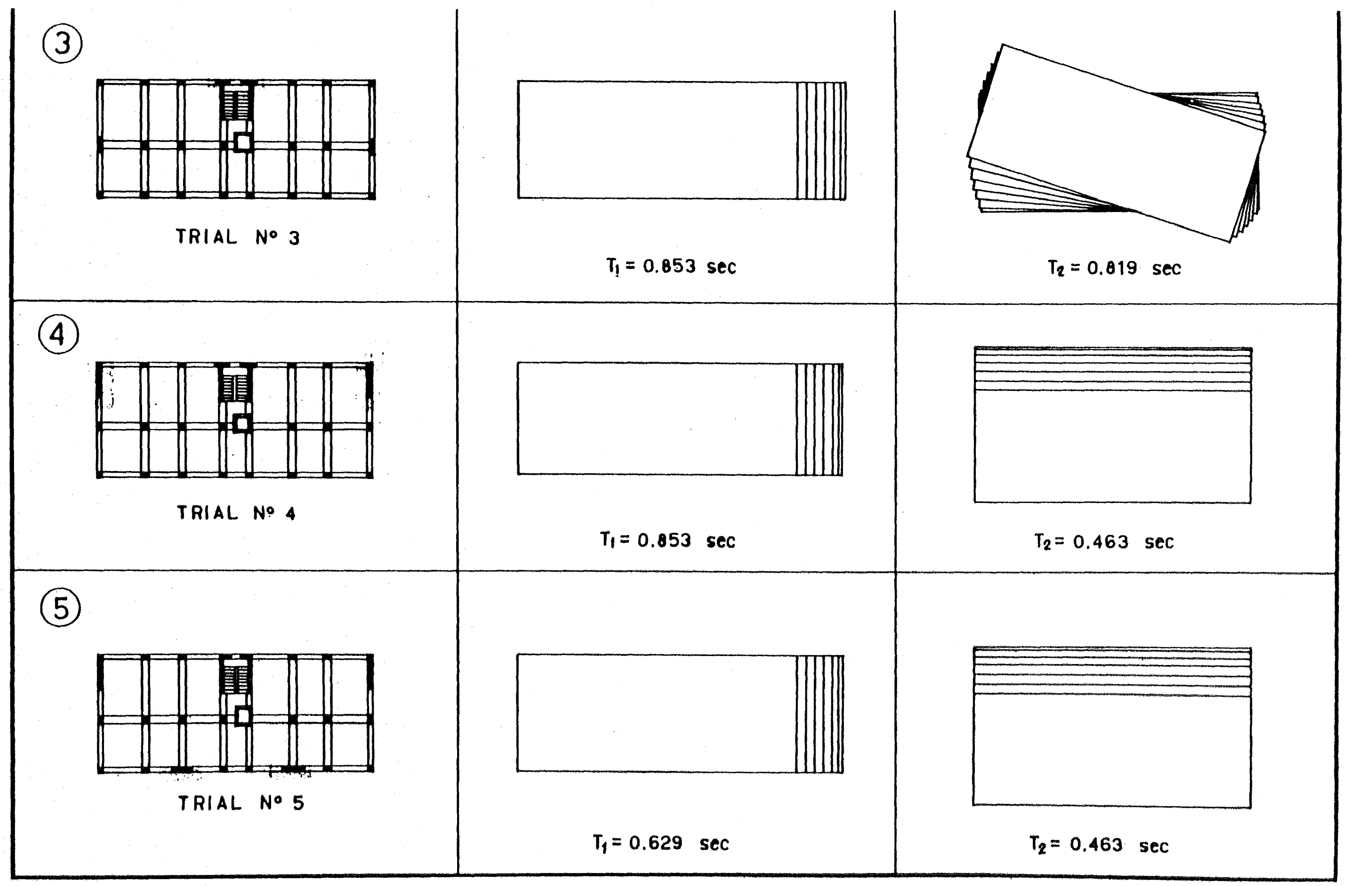


Fig. 7: Modes and periods of free oscillations: (0) original structure; (1-5) strengthened structures as described in the text.

TRIAL No.3: a), b), c), d) as above; e) thickness of the staircase outside slabs increased from 15 to 30 cm;

TRIAL No.4: a), b), c), e) as above; no d); f) two eccentric end slabs, 30 cm thick and 300 cm deep, added.

At this stage, torsional components had been eliminated, but the building was too deformable in the longitudinal direction, and the stresses were too high. Therefore a further solution was tried:

TRIAL No.5: a), b), c), e), f) as above; no d); g) two longitudinal slabs 30x200 cm added; h) the two staircases outside slabs transformed into a single wall by deep horizontal beams (Fig. 8).

This final design was fully satisfactory.

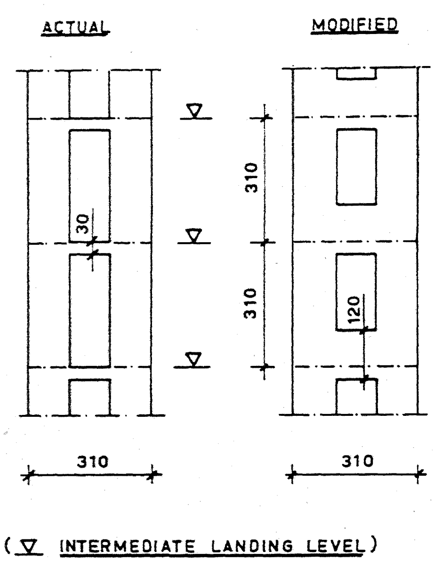


Fig.8: Staircase wall.

CONCLUSIONS

The studies briefly reported in this paper, and others still in progress, show that small modifications can be included at a small extra cost in the original building design and greatly improve its seismic response, even in the cases in which functional and/or aesthetic reasons suggest an irregular, unbalanced layout. Existing buildings can be retrofitted in a similar way by shear walls or steel bracings.

ACKNOWLEDGEMENTS

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REFERENCES

[1] A. Vignoli, G. Augusti, A. Chiarugi: "Dynamic behaviour and Seismic Upgrading of Reinforced Concrete Public Housing Buildings", 7.th E.C.E.E., Athens, Sept. 1982, Vol. 4, pp. 103-110.

[2] A. Vignoli, M. Vivoli: "Comportamento di un edificio in c.a. durante il sisma del 23.11.80 e proposte per il suo adeguamento", Giornale del Genio Civile, Rome, Vol.121, No.7/8/9/, 1983, pp.293-308.

[3] A. Vignoli: "Considerazioni ed esempi di adeguamento sismico per edifici a telaio in c.a.", Univ.Florence, Dept.Civil Engrg., UFIST/13/1983.

[4] A. Vignoli, M. Dragoni: "Un algoritmo di calcolo automatico per lo studio del comportamento sismico di strutture spaziali", Univ.Florence, Dept.Civil Engrg., UFIST/06/1983