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DUCTILITY LEVEL IN THE DESIGN OF R/C COUPLED SHEAR WALLS

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SUMMARY

The nonlinear behavior of coupled shear walls was tested, in order to improve the structure's ductility. The nonlinear finite element method and different approximate calculation methods for the elastoplastic analysis of coupled shear walls were used. The opportunity of taking into account decrease of stiffness was examined in the elastic and the plastic field. A thorough parametrical research was conducted in order to delineate the most influential quantities of the nonlinear behavior of the studied structure. A new structure with less rigid coupling beams connecting the vertical walls with a stiffening beam on the top, was tested. This technique is proposed as a possible seismic upgrading for existing structures.

INTRODUCTION

Beginning in the 1960's, numerous studies on the elastic analysis of coupled shear walls were conducted. As a result of this research the frame analysis and the continuous method were developed. Both methods assume that plastic hinges form at the ends of the coupling beams at the moment the structure reaches a limit value. In the continuous method a structure is divided into the elastic and plastic zones. Labelling of the different zones for each prescribed load value is the key problem to be solved.

This study deals with the calculation technique used in the continuous method. The following steps were carried out to:

1) compare the different analysis techniques, (Refs.1,2,3,4), and the Finite Element Method (FEM);
2) evaluate the stiffness degradation of the connecting beams and the total elastoplastic behavior of the coupled shear walls;
3) evaluate the most important quantities which affect the elastoplastic behavior of the coupled shear walls by conducting a numerical investigation using the Coull-Choo method (Ref.4);
4) evaluate the possibility to increase the structural ductility level using a top stiffening beam as a possible seismic upgrading for an existing building.

COMPARISON OF DIFFERENT ANALYSIS

The Paulay-Glück continuous method, the discrete method, and the Coull-Choo approximate method (derived from the Pekau-Gocevski method by adding simplifying hypothesis) were compared. Calculations for the two walls 18 and 24 meters heigth

were formulated so as to: (i) evaluate the effectiveness of the Coull-Choo method in different fields, (N.B. Coull-Choo applied the method to 48 and 60 meter high walls); (ii) assess the limits of application of the continuous method when compared to that of the discrete method.
In order to obtain valid homogeneous comparisons, the same collapse mechanisms were applied; in particular the criterion of 95% of the ultimate shear force for all the connecting beams was used. The two walls were considered elastic until the load corresponding to the collapse mechanism described above was reached.
In this case it was thought that the connecting beams provided the necessary rotational ductility. The Coull-Choo method was applied using constant increments of 50% of the elastic load limit in order to evaluate the plasticized end zones, the structure's behavior was observed up until the collapse mechanism occurred. The same technique was used for the Glück method applying the same actual load values.
In numerical applications, both the reduced moment of inertia and the ultimate shear force of the connecting beams was calculated using a hyperstatic scheme, for diagonally reinforced beams (Ref.5). Two walls, one composed of six storeys and another of eight storeys, were tested, (A and B, Fig.1).

Comparison of the Paulay and Coull-Choo Methods   Comparison of the two methods was carried out to quantitatively verify the results of the approximated Coull-Choo method. Therefore, the Paulay method was interrupted when the plasticization of 90% of the connecting beams was reached (stage 3). The ultimate load values obtained by the Paulay method are slightly larger (0.3%-0.4%) than those obtained by the Coull-Choo method because of used in the approximated method is smaller linearization of the laminar shear force diagram.
In the Fig.2 you can see that the plastic zone evolves quickly toward the top beam, and then extends downward, the foreseen partial collapse mechanism is always activated and the ductility level is acceptable. Taking into account the small difference in the ultimate load values, the Coull-Choo method and the Paulay method are almost equivalent.

Glück and Coull-Choo Methods   In then Glück method was used the ultimate load obtained by the Coull-Choo analysis. Diagrams in Fig.3 show that the evolution of the plastic zones is very similar. The plastic zone, identified by the Coull-Choo method, is wider than that obtained by the Glück method, until the post-elastic configurations show three different behavioral zones. The two zones become almost equal after the top beam becomes plastic, finally when the ultimate load is reached, error decreases and becomes zero.
The two methods are practically equivalent for displacements (with a difference of only 4% for the ultimate load) and perfectly equivalent for needed maximum rotational ductility (with a difference of only 2%).

Continuous Methods Paulay, Glück, Coull-Choo versus the Discrete Methods (FEM)
In order to verify the efficiency of the Coull-Choo simplified method, results obtained by the FEM (by the well known ADINA computer program) and the continuous method were compared. The FEM analysis was carried out supposing two constitutive models for two walls: (i) nonlinear with a small tensile strength (by ADINA); (ii) indefinitely linear elastic.
Results obtained (Fig.4) are sufficiently precise for wall A, also beyond the wall's elastic limit and until $W/W_{serv}=6$, (only for nonlinear concrete model). The maximum displacement difference, corresponding to the Paulay's third stage load is about -40% using hypothesis (i) and +25% using hypothesis (ii).
The comparison of wall B is generally positive, but quantitatively unsatisfactory. In fact, the displacements obtained by the ADINA are smaller using both constitutive hypothesis, with differences of 30-40%.

STIFFNESS DEGRADATION OF THE CONNECTING BEAM

The connecting beams are usually squat elements with a ratio span/height less

than 2. They are quite sensitive to shear force and show notable cracks as stress increases. The influence of this phenomenon on the elastoplastic behavior of coupled shear walls A and B (Fig.1) was examined.
In Ref.7 an extensive analysis was carried out on influence of stiffness of connecting beams on elastoplastic behavior.
The ultimate laminar shear force was kept constant for each wall. Structural analysis were conducted using a collapse mechanism corresponding to the plasticization of 90% of the connecting beams. Results are briefly summarized. As the connecting beams' stiffness decreases the linear-elastic structural behavior is extended, i.e. the collapse mechanism is reached at larger loads. An understimation of the connecting beams' stiffness can lead to an eschewed evaluation of the rotational ductility thereby calculating a dangerous overestimation of the structure's ultimate load. The use of sophisticated numerical techniques to evaluate the structure's degradation can be useless when one considers the notable uncertainty regarding the definition of the connecting beam's stiffness and the lack of more precise experimental data.

PARAMETRICAL ANALYSIS

The elastoplastic behavior of coupled shear walls is influenced by numerous geometrical parameters, therefore it is difficult to determine the most important ones. The relative stiffness coefficient ß (a-dimensional) was used as the fundamental parameter. It was introduced by Rosman for linear analysis, but ß has proven to be useful also in nonlinear field.
The parametrical analysis was conducted for a 12 storey coupled shear wall (Fig.1, C). Some results are described below; for complete results see Ref.7.
The coupled shear walls' elastoplastic behavior was analyzed by varying the: 1) connecting beam's height; 2) ultimate laminar shear force; 3) thickness.
Results show that the very height connecting beams are cheaper to use because they need less reinforcement, but their post elastic behavior is not satisfactory. In particular they are prevented from reaching ultimate load because of their strong need for rotational ductility. When using more flexible connecting beams ultimate load values can be reached, but they need stronger reinforcements.
The ultimate shear force of the connecting beams was assessed by varying the reinforcements of the coupled shear walls with h_t=60 cm. Results show that the structural ductility level is independent of the ultimate shear force. This result is valid only if the two walls can elastically absorb the stresses before plasticization of almost all the connecting beams occurs. The external ultimate load is dependent almost exclusively on the reinforcements of the connecting beams. This result, if confirmed by more accurate theoretical and experimental analysis, is very important for applications. In fact, given a certain value of the maximum rotational ductility, the ultimate load value can be determined by simply dimensioning the connecting beams.
The total wall stiffening, obtained by increasing the thickness, can be useful only for: reducing the structure's displacements, avoiding the instability phenomena and increasing the vertical resistance, but not for improving elastoplastic behavior.

THE TOP STIFFENING BEAM

Two opposing needs can be seen in the previous paragraph; one calls fairly rigid connecting beams, while the other calls fairly rotational ductility to obtain an adequate post elastic behavior. This behavior can be improved by redistributing the rigidity inside the wall itself. The top stiffening beam, as suggested in (Ref.4) can be used to improve the elastic behavior of walls with flexible connecting beams. Some numerical applications were conducted using the Coull-Choo method in order to verify the elastoplastic behavior of the coupled shear walls. The top beam's effectiveness was assessed in order to obtain data for the design. A numerical analysis was then conducted to determine the best choice of the ratio $\gamma_o = E_sI_s/E_tI_t$ (E_sI_s=flexural rigidity of top beam; E_tI_t=flexural rigidity of connecting beam). The test was conducted with 0, 1, 8 and ∞ γ_o values; 0 corresponds to an indefinitely flexible top beam, and ∞ to an indefinitely rigid top beam. Results were analyzed in both the elastic and the plastic field.

Elastic behavior Two 12 storey walls, derived from the C wall (Fig.1) were tested. The height of the connecting beams were respectively 40 and 60 cm; the Rosman coefficients were 7.04 and 11.15. The structural analysis with a triangular load distribution and with 40 cm height beams showed that as the top beam's stiffness increased: (i) horizontal displacements were almost the same; (ii) the laminar shear force (Fig.5) variation was evident only in the upper part of the wall; (iii) the results corresponding to γ_o=8 and $\gamma_o=\infty$ are not to much different. The analysis of the wall with 60 cm height connecting beams showed that the top beam's influence is numerically negligible.

Elasto-plastic behavior In order to take into account the structure's degrading phenomena, both the connecting beam and the top beam's stiffness were reduced to 70% of its non-cracked value. No limit was applied to ultimate shear force of the top beam. In fact, since the top beams do not influence the elastic behavior, their reinforcements were dimensioned according to the required post-elastic characteristics. The same collapse mechanism, used for the previous analysis was adopted. Fig.6 show the load-displacement diagram for the different values of the γ_o parameter. When γ_o varies from 1 to 8, the wall's behavior changes abruptly. In fact, both the ultimate load and the structural ductility values decrease. As $\gamma_o \geq 8$ these two values slightly increase, and the structural behavior corresponds to the case of an indefinitely rigid top beam. Fig.6 show the interesting relationship between needed maximum rotational ductility and the ratio W/W_{serv}. The presence of the top beam reduces the rotational ductility need for the same applied load. Maximum values decrease from 5.72 (γ_o=0) to 4.83 (γ_o=1) and to 2.94 (γ_o=8) with 16% and 49% reductions. The advantage of using stiffening beams is evident. In fact the ultimate load corresponding to the collapse mechanism (i.e. 90% beam plasticization) can not be reached with conventional steel arrangement for connecting beams ($\mu_r \leq 4$). On the contrary using a top stiffening beam (h_s=80 cm) 90% connecting beams plasticization occurs, the ultimate load increases ($\mu_r \leq 4$), the structural ductility decreases (18%), the axial forces in the walls increases while the bending moment decreases.
For design purpose, the same 12 storey wall was tested in two different situation: (i) h_t=60 cm and γ_o=0, (ii) h_t=40 cm and γ_o=8. The top stiffening beam was 80 cm height and the connecting beam's ultimate shear force was kept constant. Load displacement diagrams, (Fig.7) indicate a 20% increase in the ultimate load. When the connecting beam's rotational ductility is equal to 3, there is an increase of more than 50%. This result is the direct consequence of the notable reduction in the needed rotational ductility, which allows the 90% connecting beams to become plastic (Fig.7). The structural ductility of walls with 60 cm height connecting beams is equal to 2.97. When a connecting beams' rotational ductility limit is equal 3 the structural ductility is equal to 2.08 for h_t=60 cm and 2.11 for h_t=40 cm.

CONCLUSIONS

Results indicate that the exact continuous method (Paulay & Glück) and the approximate continuous method (Coull & Choo) are practically equivalent. The two method provide: adequate approximate internal forces, a correct evaluation of the needed maximum rotational ductility, and of the displacements. It is evident that the calculation of the parameters describing the structure's behavior is not influenced by the approximate evaluation of the plasticized zone. This characteristic is due to the slight difference between the actual and the approximated laminar shear force distribution. Moreover the step-by-step procedure is such that the results corresponding to each load increase are independent of previously values.

Consequently there is not any error spreading. The Coull-Choo method is simple, quite accurate, and it can be efficient for preliminary structural design.

The conducted analysis regarding the influence of the connecting beams stiffness degradation which occurs after the plastic field is reached indicated that it is necessary to accurately chose the reduced stiffness and to consider the shear deformability of the connecting beams.

The parametrical analysis showed the importance of the wall-connecting beams relative stiffness in determining the rotational ductility. Results indicate that the post elastic behavior of the coupled shear walls principally depends on the relative stiffness Rosman coefficient. The structural response of the system does not depend on the ultimate shear force capacity of the connecting beams.
Elaboration of the results provided a diagram μ_r-ß (Fig.8). This diagram indicates that, with a coefficient ß greater than 7 and with rotational ductility equal to 4, 90% beam plasticization can not take place. Moreover, as the Rosman coefficient increases, the percentage of the connecting beams becoming plastic at the collapse configuration decreases quickly. When the rotational ductility equals 12 and $\beta \leq 10$, plasticization of about 100% of the connecting beams can take place. Using the standard values of the Rosman coefficient and $\mu_r=12$, the percentage of plasticizated beams at the collapse configuration is always greater than 80%. A 90% plasticization can only be achieved when the ß coefficient values are less than 15 ($\mu_r \leq 12$). The necessity of using diagonal reinforcements in the design of the connecting beams is evident because they provide protracted post-elastic behavior. More attention must be placed on the geometrical dimensions of the coupled shear wall, because a large value for ß reduces the possibility of ductile behavior.

Coupled shear walls can be stiffened by a top beam. It is an adequate system *for: upgrading existing structures to seismic codes; restoring structures when* they are crack. Numerical results showed the validity of the design method adopted for conventional reinforced connecting beams which provide low level of rotational ductility. The top stiffening beam proved to be useful only when applied to coupled shear walls with connecting beams with a low flexural rigidity.

ACKNOWLEDGEMENTS

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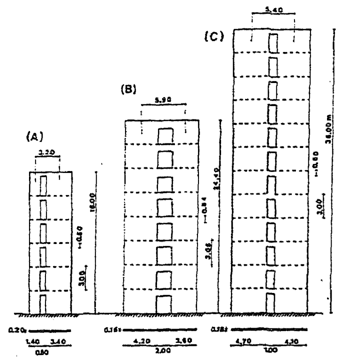

Fig.1 Coupled shear walls

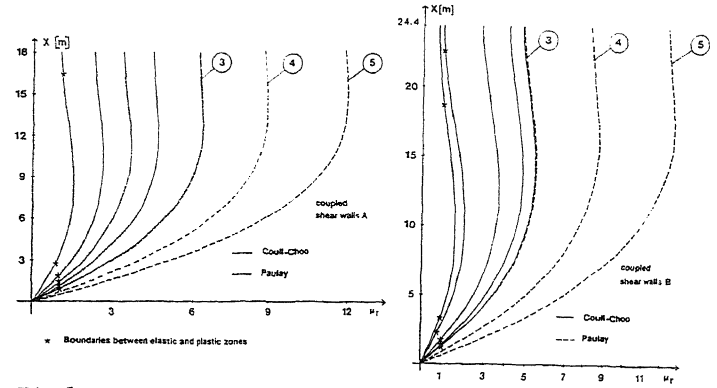

Fig.2 Comparison of the Paulay and Coull-Choo methods

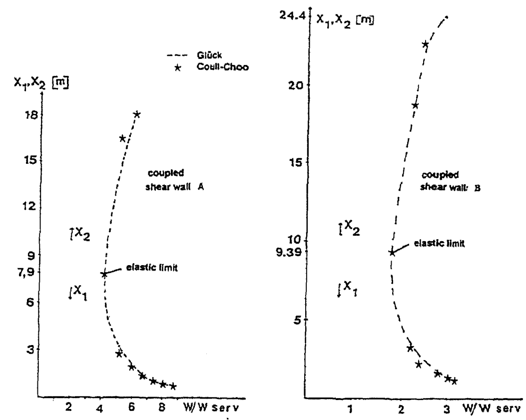

Fig.3 Comparison of the Glück and Coull-Choo methods

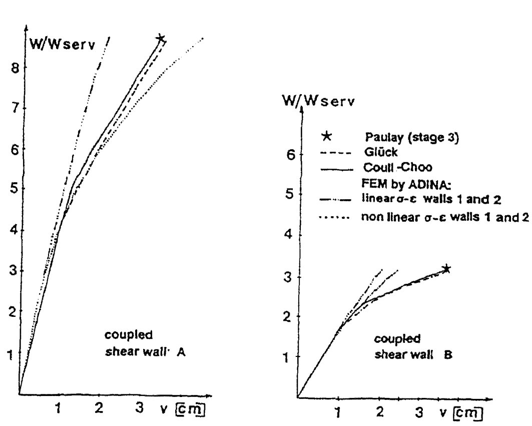

Fig.4 Comparison of the continuous methods and the FEM

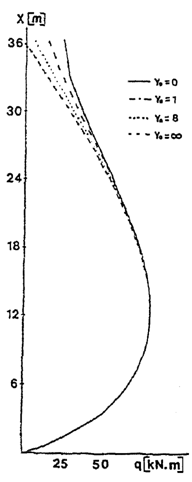

Fig.5 Top stiffening beam's design: laminar shear force

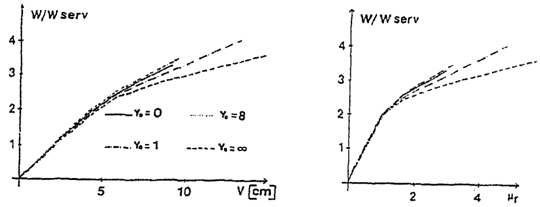

Fig.6 Top stiffening beam's design: structural and rotational ductility

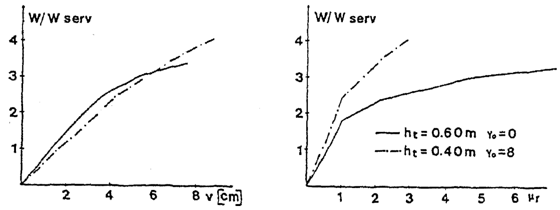

Fig.7 Comparison of alternative design choices

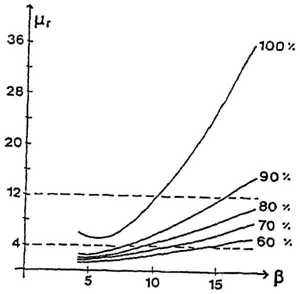

Fig.8 Maximum rotational ductility and Rosman coefficient