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Analysis of the Seismic Behaviour of RC Structural Walls with Rectangular Cross-Sections

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ABSTRACT

The coordinated research of the University of Ljubljana and the Institute of Testing and Research in Materials and Structures was carried on. Ten structural walls were tested at the Institute (companion paper by M. Tomaževič et al) and analytical support was offered by the University. It included capacity prediction using neural network approach, cyclic response prediction using multiple-vertical-line-element macro model for structural walls, post-experiment evaluation of the proposed procedures, and the analysis of a similar wall, designed according to Eurocode 8. While many parameters were predicted with acceptable correlation with the test, some (in particular the effect of confinement of the free edges) are difficult to predict. The deficiences of the proposed methods were identified and some improvements were proposed. Eurocode was found to be effective in providing seismic safety to the analysed wall.

INTRODUCTION

Most of the multi-storey appartment buildings and offices in Slovenia include RC structural walls. Special feature of this buildings is a high wall-to-floor area (Fig. 1). Due to the building technology, boundary columns (barbell walls) are not used. Experience during recent earthquakes has indicate good response of such buildings to earthquake loading. However, some cases (Fig. 2) indicate that there are still many problems to be solved. It is particularly important to solve these problems now, when new Eurocode structural standards are being adopted by most European countries (including Slovenia).

The quantitative prediction of the seismic capacity of a RC structural wall (in terms of shear strength, deformations, and failure types) relies, besides on the non-linear mathematical models, almost exlusively on experiments and empirical expressions. Therefore, a set of experiments was performed at the Institute for Testing and Research in Materials and Structures in Ljubljana as the basis of the research project. Ten specimens with the same geometry (rectangular cross-section) and dimensions, reinforced in five different ways (with and without vertical steel, concentrated at the edges of the wall and with and without

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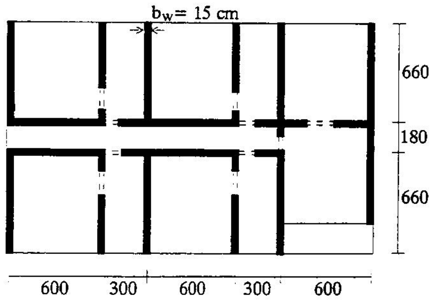


Fig. 1 Plan of a typical apartment building in Slovenia

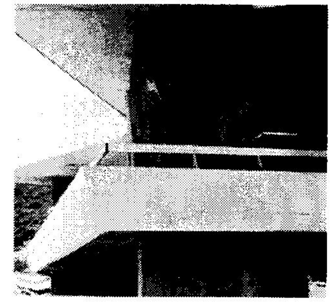


Fig. 2 Damage to a structural wall during the 1979 Montenegro earthquake

confining reinforcement) were cyclically tested at two different levels of axial loads (10 % and 20 % of the compressive strength). The details of the experiments are given in the companion paper (Tomaževič et al, 1995) and recapitulated in Table 1.

Since the number of experiments is typically very limited, a reliable and efficient analytical tool is needed to predict inelastic seismic behavior of structural walls. Two different approaches (capacity prediction using neural network approach, and cyclic response prediction using the multiple-vertical line-element macro model for structural walls), which were used in advance of the experiments, are presented in the paper.

Table 1. Basic data of the tested walls

Type	Identification	Mesh reinforcement	Concetrated reinforcement	Confining reinforcement
1	SW00Ni*	0.26 %	-	no
2	SW23Ni	0.26 %	2.3 %	no
3	SW23Ci	0.26 %	2.3 %	yes
4	SW60Ni	0.38 %	6 %	no
5	SW60Ci	0.38 %	6 %	yes

* i = 1 for low axial force (see the companion paper)
i = 2 for medium axial force

CAPACITY PREDICTION USING NEURAL NETWORK APPROACH

There is a lack of understanding about the dependence of the observed behavior of structural walls on variables such as cross-sectional shape, reinforcement distribution, axial compression, and loading histories. Empirical treatment of the complex phenomena as the behavior of RC structural walls is, introduces adaptive techniques, known from the application of the artificial neural networks in different science areas. A non-parametric multidimensional regression, or so called intelligent, neural network-like system, based on this method, has been developed for the prediction of the capacity of RC structural walls. Explanation and verification of the method are described by (Peruš, Fajfar & Grabec, 1994). It should be mentioned here that the application of the method needs a data base which contains data on results of experiments on the structural elements under consideration. The original data base used in the presented study was compiled from available literature, and it includes data from laboratory tests carried out on 262 structural walls.

First, the prediction was done in advance to the test (see "prediction before" in Table 2), however, measured material characteristics were used. Than the new experimental data were included into the data base. The new predictions were obtained (see "prediction after" in Table 2), based on special procedure proposed by (Peruš, Fajfar & Grabec, 1994) for the validation of the method. Each capacity for each wall was predicted in a way, where the wall under consideration was temporarily removed from the data base.

The results are given in Table 2. The type of failure (shear strength) was successfully predicted. It was not possible, however, to predict drift capacity, which was much overestimated in comparison with the test, and the effect of confinement was not identified correctly. There are several reasons for that. The original data base included mostly walls with barbell cross-section, and less walls with flanged or rectangular cross-section. Some parameters (like loading history or setup of the test) were not included in the base. Drift capacity of the tested walls as well as the effect of confinement were low in comparison with the typical expectations. This could indicate the deficiences in the local practice.

As the results show, new data improve the predictions, therefore the future work should be concentrated on the improvement of the data base.

Table 2: Predicted and experimental results.

SPEC.	*SHEAR STRENGTH*		*SHEAR DEMAND*	*FAILURE TYPE*			*DRIFT*		
	prediction		***test***	***prediction***		***test***	***prediction***		***test***
	before	***after***		***before***	***after***		***before***	***after***	
SW00N1	94 kN	94 kN	40 kN	flexural	flexural	flexural	2.7%	2.3%	1.3%
SW00N2	118 kN	118 kN	63 kN	flexural	flexural	flexural	2.1%	1.1%	0.6%
SW23N1	122 kN	122 kN	65 kN	flexural	flexural	flexural	2.0%	2.0%	0.8%
SW23N2	168 kN	168 kN	87 kN	flexural	flexural	flexural	1.8%	1.5%	0.6%
SW23C1	122 kN	122 kN	65 kN	flexural	flexural	flexural	1.9%	1.3%	0.9%
SW23C2	180 kN	180 kN	84 kN	flexural	flexural	flexural	1.7%	0.7%	0.8%
SW60N1	162 kN	162 kN	107 kN	shear-flex	flexural	flexural	1.7%	1.3%	1.1%
SW60N2	180 kN	180 kN	111 kN	shear-flex	flexural	flexural	1.7%	0.8%	0.6%
SW60C1	175 kN	175 kN	110 kN	shear-flex	flexural	flexural	1.4%	1.3%	1.3%
SW60C2	180 kN	180 kN	118 kN	shear-flex	flexural	flexural	1.1%	0.8%	0.7%

SEISMIC BEHAVIOR PREDICTION USING INELASTIC CYCLIC ANALYSIS

The modified DRAIN-2D program was used to predict the inelastic cyclic behavior of the analysed walls. Multiple-vertical-line-element-model (e.g. Fischinger, Vidic & Fajfar, 1992; Figs 3) was used in the analysis. In the model, a series of vertical springs simulates the flexural behavior and a horizontal spring models the shear behavior of the wall segment.

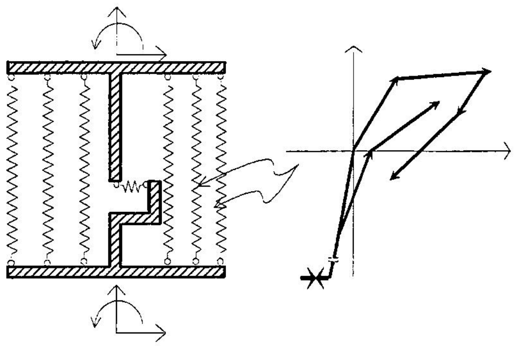


Fig. 3 Analytical model for structural walls

The characteristics of the springs were based on the specified material data. Since DRAIN-2D originally assumes unlimited ductility, the ultimate state of the wall was defined on the basis of the deformation in the vertical springs (10 % in tension and 3.5 ‰ in the compression of the unconfined edges). For confined edges, the ultimate deformation of the concrete in compression (5.7 ‰) was calculated according to the Eurocode standard (EC8, 1994). The effect of confining was rather small, considering the seemingly strong hoops. The shape of the hoops (without cross-ties), however, appears to be relatively inefficient.

The comparison of the analytically predicted and experimentally observed behavior for the wall with the concentrated reinforcement ratio 2.3 % is given in Fig. 4. First impression is that the correlation is not good at all. Looking more carefuly, however, one could observe that the ultimate strength and deformation were predicted relatively well. It should be taken into account that the specified material characteristics (which were 16 - 35 % lower than the actual ones for the reinforcement and even more in the case of concrete) were used in the analysis. Furthermore, DRAIN-2D can not simulate post-critical behavior of the structure.

It should be noted that the analysis has always indicated failure of the compression edge, which was not always the case in the experiment. This could indicate that the EC8 procedure for determining the ultimate capacity of the confined concrete might be conservative.

There is an obvious discrepancy in the shape of the hysteretic loops. The first reason is the already mentioned incapability of the DRAIN-2D to simulate the post-critical behavior. The other reason is that (expecting flexural behavior of the wall), elastic shear behavior was assumed in the analysis. However, shear cracking appeared rather fast. When shear cracking force according to (Wight, 1985) was introduced in the horizontal spring model, the results improved (Fig. 5).

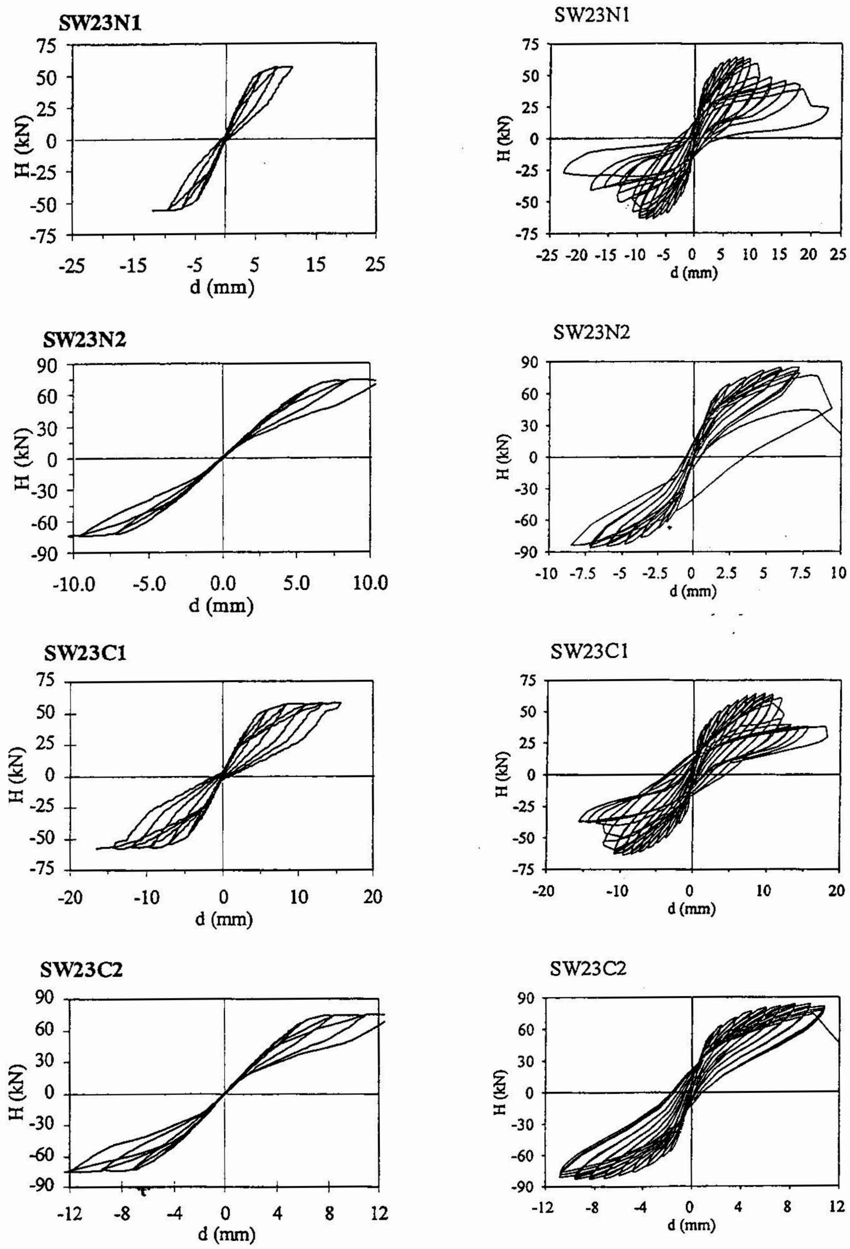
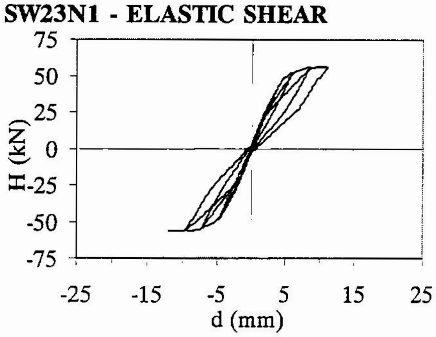


Fig. 4 Comparison of the analytical and test results
H ... base shear
d ... top displacement



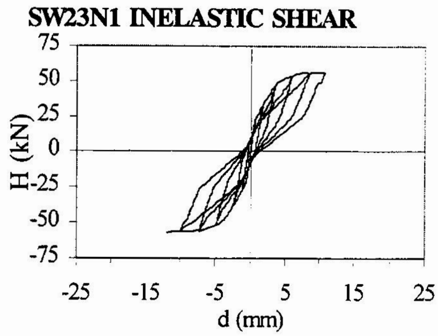


Fig. 5 The influence of the inelastic shear behavior on the response

ANALYSIS OF A TYPICAL WALL DESIGNED ACCORDING TO EUROCODE-8

Eurocodes are intended to establish a set of common rules as an alternative to the differing rules in force in the various Member States in the EC. Adaptation of the common rules to the respective national safety level will be subjected to national responsability.

The test specimens were reinforced within the limits required by the current codes in Slovenia. Eurocode-8, however, imposes more severe demands on walls with rectangular cross-sections. For comparison a heavily loaded wall was designed according to the both codes and analysed with the presented multiple-vertical-line-element model.

The cross-section of the rectangular wall (0.2/5.0 m) at the bottom of an idealized 10-story building was studied. A very low wall-to-floor area ratio (1 %) in comparison with the Slovenian practice (typically 1.5 - 4 %) and severe seismic conditions (maximum ground acceleration a_{gmax} = 0.4 g; typically 0.2 g) were foreseen to get extremly severe loading on the wall.

EC8 requires much more longitudinal and transversal reinforcement at the edges of the wall (Fig. 6). In addition to that, one should increase the thickness of the wall (to about 30 cm) following the EC8 requirements. In the analysis, however, the same thickness (20 cm) was taken into account for both codes.

A relatively simple method for the non-linear seismic analysis of reasonably regular buildings oscillating predominantly in a single mode (N2-method) was used in the analysis. N2 is a **N**on-linear method which combines **2** different models: the MDOF model for non-linear static analysis and the equivalent SDOF model for non-linear dynamic analysis (Fajfar & Fischinger, 1988). The loading was defined by the elastic spectrum according to the EC8 standard and a_{gmax} = 0.4 g. Due to the space limitations, only the most important results are summarized in Table 3.

The strength of the wall has not increased proportionally with the boundary reinforcement and, as known, the maximum displacement does not depend very much on the strength.

Local damage was estimated by the damage index based on the Park-Ang proposal (1984) and further modified by (Fajfar & Gašperšič, 1994). The procedure was properly adjusted to structural walls. The yield and ultimate deformations of the boundary springs were used to determine the yield and ultimate rotations, respectively. Three different values of the parameter β in Park-Ang model (0.05, 0.15 and 0.5) were taken into account. Lower values of β apply for structures with good detailing (e.g. those designed according to EC8). Medium values of β might be appropriate for the Slovenian practice.

From the results (Table 4), one can conclude that even in the case of the analysed extreme loading, no collapse (DM = 1.0) would probably occur in the wall designed by either of the two codes. However, damage in the wall, designed according to the Slovenian code, would be severe. In addition to that, the authors realize that out of plane buckling was not taken into account in the model.

Table 3. Results of the inelastic analysis

	SLO	EC8
Base shear capacity	714 kN	1090kN
Maximum top displacement demand	29.52 cm	29.48 cm
Required ductility of the equivalent SDOF system	2.6	1.7

Table 4. Calculated damage indices DM (DM = 1.0 indicates collapse)

	SLO	EC8
$\beta = 0.05$	0.44	0.23
$\beta = 0.15$	0.55	0.27
$\beta = 0.50$	0.93	0.42

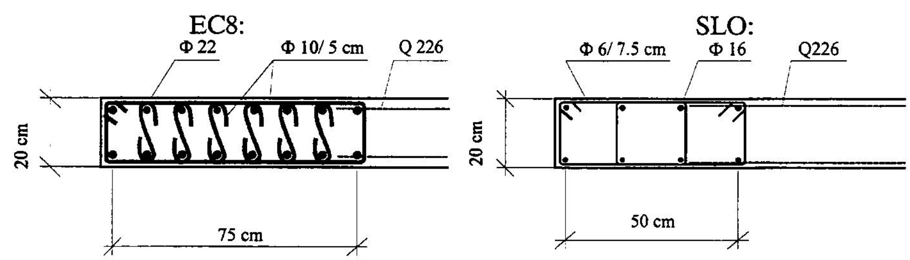


Fig. 6 Reinforcement at the edges according to Eurocode-8 (EC8) and Slovenian practice (SLO)

On the other hand the average local conditions in Slovenia are much more favourable (2 - 4 % wall-to-floor area is typical and $a_{gmax} \leq 0.2$ in most areas). In such conditions EC8, which is obviously effective even in the extreme case (DM ≐ 0.25), might be conservative.

CONCLUSIONS

Two promising methods to predict inelastic seismic behavior of RC structural walls were analysed. Predictions were made in advance and than tested against experimental results.

Neural network could have been a very powerful technique, providing that a good data base is established. In our case, however, there were only few data about walls with rectangular cross-section in the base. Therefore, we failed to predict some parameters (in particular the effect of confinement at the edges of the walls) successfully. New data improve the prediction considerably.

Multiple-vertical-line-element model was quite successful in predicting ultimate strength and deformations of the analysed walls. The relatively small effect of confinement, observed in the test, was successfully predicted. There are problems, however, how to realistically include inelastic shear behavior and out of plane buckling into the model.

In comparison with the Slovenian practice, Eurocode-8 imposes more severe requirements. They have been effective in providing seismic safety to a wall with severe seismic loading. It seems, however, that EC8 might be conservative for structures with high wall-to-floor ratio in the regions with moderate seismic intensity.

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REFERENCES

EC8 1994, Eurocode 8 - Design provisions for earthquake resistance of structures, ENV 1998, CEN, Brussels.

Fajfar, P. Fischinger M. 1988. N2 - A Method for Nonlinear Seismic Analysis of Regular Buildings. Proc. 9th WCEE, Tokyo, Maruzen, vol. V, 111-116.

Fajfar, P., Gašperšič, P. 1994. A Method for Prediction of Seismic Damage in RC Buildings. Abstracts 10th ECEE, Vienna, Balkema, vol. 1 (paper to be published).

Fischinger, M., Vidic, T., Fajfar, P. 1992. Nonlinear Seismic Analysis of Structural Walls Using the Multiple-vertical-line-element Model, Proc. Workshop Nonlinear Seismic Analysis and Design of Reinforced Concrete Buildings (Eds. Fajfar P. and Krawinkler H.), Bled, Elsevier, 191-202.

Park, Y.J., Ang, A.H-S., Wen, Y.K. 1984. Seismic Damage Analysis and Damage-limiting Design of R.C. Buildings, Structural Research Series No. 516, Univ of Illinois, Urbana.

Peruš, I., Fajfar, P., Grabec, I. 1994. Prediction of the Seismic Capacity of RC Structural Walls by Non-parametric Multidimensional Regression. Earthq. Eng. & Struct. Dyn., vol. 23, 1139-1155.

Tomaževič, M.,Capuder, F., Lutman, M., Petkovič, L. 1995. Influence of Distribution of Reinforcement on Seismic Behavior of RC Shear Walls. Proc. 7th CCEE, Montreal (to be published).

Wight, J.K. (Editor) 1995. Earthquake Effects on Reinforced Concrete Structures, ACI.