BENCHMARK ANALYSIS OF A STRUCTURAL WALL

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SUMMARY

Blind prediction of the seismic response of a five-story, lightly reinforced cantilever structural wall with rectangular cross-section subjected to three earthquakes of different intensity was made. The main objective of the study was to check the ability of a relatively simple macro element (multiple-vertical-line-element) and a standard computer code (DRAIN-2D) to model global parameters of the wall response. Analytical prediction was influenced by some parameters (e.g. initial stiffness, strain hardening, damping, and sequence of the three tests) which were difficult to predict in advance. Nevertheless, this quite simple analytical tool was able to predict the response with acceptable accuracy (stiffness and strength prediction was good, failure estimation was close). It is believed that (regarding all the uncertainties of the problem) further sophistication of the model may not substantially improve the results.

INTRODUCTION

Present capability of realistic and practical modelling of non-linear static and dynamic seismic response of RC structural walls is still limited. Therefore, the international benchmark study, organised by the CAMUS working group under the auspices of French Association of EE [CAMUS, 1997], was a fine opportunity to improve the relevant knowledge. The IKPIR institute participated as one of the 11 research organisations making blind prediction of the seismic response of a five-story cantilever structural wall subjected to three earthquakes of different intensity.

The main objective of the presented study was to check the ability of a relatively simple macro element and a standard computer code to model global parameters of the wall response (e.g. global failure mechanism, maximum displacements, ultimate strength, uplift of the tension corner and rocking).

In the past 15 years, the authors have got some experience in using macro models in the analysis of the seismic response of structural walls. Macro models consist of a finite number of discrete springs following prescribed force-displacement relationships. They attempt to describe overall behaviour by means of an appropriate idealisation. In the presented study a multiple-vertical-line element model MVLEM [Fischinger 1992] was used. The element was incorporated into a modified version of the DRAIN-2D program. The original version of this standard computer code has been available for engineering community since early seventies [Kanaan 1973]!

Although the model had been successfully applied in several post-experiment studies before [Fischinger 1992], this was the first time to make a blind prediction. Several dilemmas in choosing appropriate parameters of the model in advance arose and some possible pitfalls of mathematical modelling were identified. Therefore, several short parametric studies were made to study influences of the element mesh, damping, sequence of testing, and inelastic shear deformations. Using the information gained by these parametric studies, the so-called "basic model" was defined. Using this model the experiments were simulated in advance. The time histories for horizontal and vertical displacements as well as shear forces and bending moments were computed. Global failure mechanism was estimated. After the organisers of the benchmark study had made known the results of the experiments [Combescure et al., 1998], the comparison of the presented analytical prediction and

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experimental results has shown an acceptable correlation. In the case of discrepancies the causes were studied in some more depth.

DESCRIPTION OF THE EXPERIMENT AND TEST SPECIMENT

"CAMUS" (Conception et Analyse des Murs sous Seisme) benchmark study was co-ordinated by the French Commission for Nuclear Energy. A 5-story RC cantilever wall in scale 1:3 was subjected to a series of three artificial earthquakes.

The wall (Fig. 1) was designed according to the French codes with rather unusual distribution of the reinforcement. Longitudinal reinforcement was light. It was placed only in the boundary areas and in the centre of the wall (acting as a sort of dowel). There was no horizontal reinforcement, except for stirrups around the bundles of the longitudinal reinforcement. It was a special challenge to analyse such a wall with the chosen model, which had never been used for similar structures before.

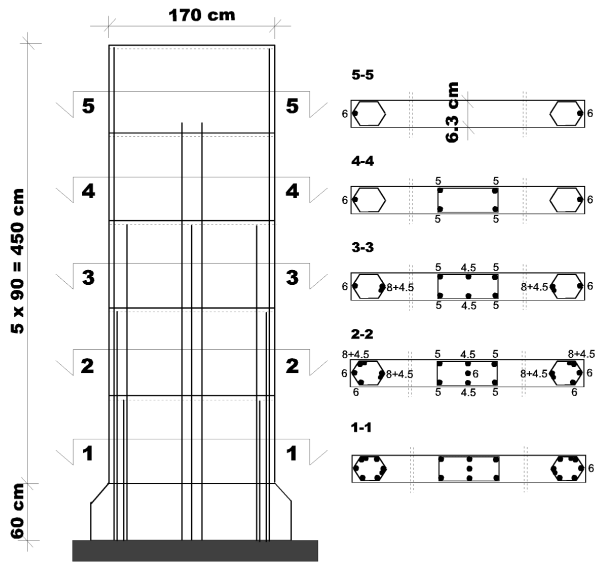

Figure 1. CAMUS cantilever wall

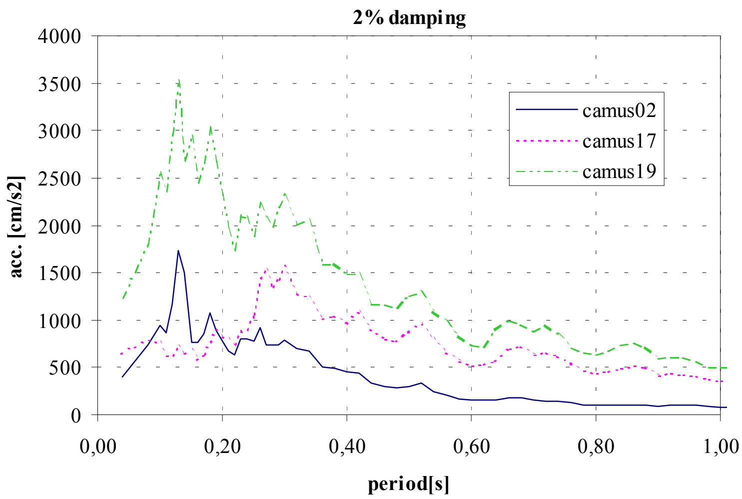

Figure 2. CAMUS spectra

Maximum ground accelerations of the artificial earthquakes amounted to 0.24g (CAMUS02), 0.40g (CAMUS17) and 0.71g (CAMUS19). The shape of the spectra for these three accelerograms was quite different (Fig. 2). The sharp peak of the CAMUS02 spectrum near the first natural period of the wall (calculated on the basis of the uncracked sections) is to be noted. It might have an important influence on the behaviour (and damage) of the wall during the first test at the lowest level of excitation.

THE MULTIPLE-VERTICAL-LINE-ELEMENT-MODEL (MVLEM)

The physical model

MVLEM [e. g. Vulcano 1989] is a macro model (Fig. 3) consisting of several springs, which monitor cyclic force-displacement relationships. Several parallel vertical springs represent the axial and flexural stiffness of the central panel as well as of the boundary columns. The horizontal spring models the shear behaviour of the wall member.

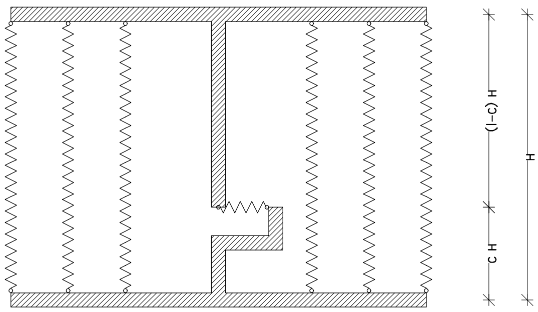

Figure 3. Multiple-vertical.line-element-model (MVLEM)

The entire wall is modelled as a stack of n MVLEM wall elements. The flexural and shear deformations are separated in each MVLEM. All shear behaviour is concentrated in the horizontal spring, which is placed at the height $c \times h$ ($0 < c < 1$). The horizontal shear displacement on the top of the stack does not depend on c. Flexural deformations, however, do depend on c as well as on n. The results are particularly sensitive in the plastic hinge zones where even small gradients of moments can cause highly non-linear distributions of curvature. The problem can be solved by stacking of the elements in the hinge zone as well as by using lower values of c (e.g. c=0.3)

Hysteretic models

Simple rules for axial force – displacement relationship (Fig. 4) were used in the study. Shear-slip hysteresis could be used for shear behaviour. Since the geometry and reinforcement of the walls indicated flexural behaviour, only elastic shear behaviour was considered in the basic model.

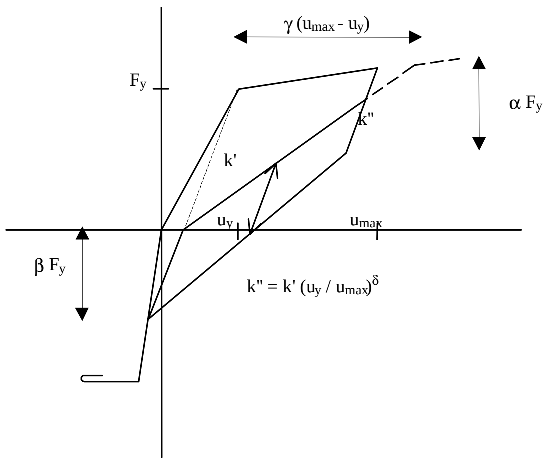

Figure 4. Vertical spring behaviour

MODELLING OF THE WALL

Wall geometry (element mesh)

The wall was modelled as a stack of 25 MVLEM elements. The changes in longitudinal reinforcement, the location of floors and the location of strain gages were considered in determining the mesh. At the beginning shorter elements had been planned at the base of the wall only, where more yielding is usually expected. However, subsequent re-design, using French design response spectrum, indicated that, due to the cut-off of the longitudinal reinforcement, the bending moment capacity closely followed the design demand over the entire height of the wall (Fig. 5). This indicated the possibility of yielding in the upper stories. Shorter elements at the construction joints at each floor level, which had been originally planned to model strain gages only, were considered appropriate to model yielding in higher stories, too.

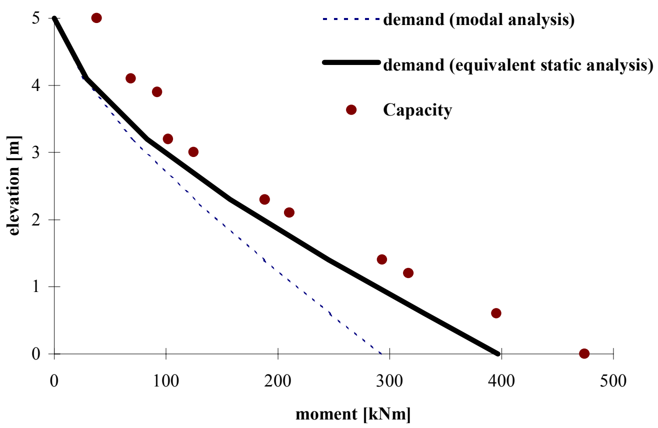

Figure 5. Bending moment capacity versus design demand

Modelling of an individual MVLE

According to the previous experience, 6 vertical springs were chosen for each MVLE. Each vertical spring was modelled as an RC truss element. Only the contribution of concrete was considered to determine the strength and stiffness in compression. Only the contribution of reinforcement was considered to determine the strength in tension (the two springs without reinforcement had no tensile strength). This supposition was considered acceptable at later phases of the response. The contribution of both, concrete and reinforcement, was considered to determine the stiffness in tension. The horizontal spring was located at 30% of the height of the element.

THE CHOICE OF THE PARAMETERS OF THE MODEL

Only one analytical solution had to be submitted to the organisers of the benchmark study. Several dilemmas arose and they revealed the possible pitfalls of mathematical modelling. Therefore, several comparisons were made first, to evaluate some of the main parameters used in the analysis.

Pre-cracking (initial natural frequencies)

The first natural frequency of the wall (7.24 Hz), measured prior to the experiment was reported in advance by the benchmark organisers. In the analytical prediction of the natural frequencies, the wall was modelled as a simple beam-column cantilever. The uncracked gross concrete sections were considered. The calculated first natural frequency (9.46 Hz) was considerably lower than that, reported in the benchmark data. This indicated a possible influence of pre-cracking of the wall. Such pre-cracking associated with minor but invisible damage, seems to be typical for most test specimens as well as for any reinforced concrete structure in general. However, the information on pre-cracking is typically not available. In addition, it could affect only the first stage of the CAMUS02 response. Later, the wall cracked anyway. Therefore, we still decided to consider the uncracked gross sections without any reduction of stiffness at the beginning of the response-history analyses.

Viscous damping

It is very difficult to assume the level of viscous damping and this parameter may have an important influence on the numerical prediction. Two common values (2% and 5%) were tested in preliminary studies. The comparison for the CAMUS17 record is given in Fig. 6. The difference is quite important. In the case of the stronger CAMUS19 record, the hysteretic damping was important in comparison with the viscous damping. So, at the end of the response the difference in displacements obtained for the two damping values, was smaller. Considering the fact that there were no secondary (non-structural) elements to increase the damping of the tested wall, we decided to use 2% of damping in the final analysis. Later, this proved to be a right decision. Even with only 2% of damping the numerical prediction still underestimated the observed displacements.

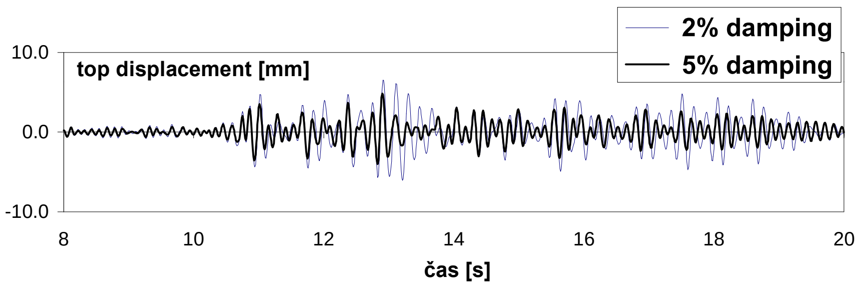

Figure 6. Displacement time-history, CAMUS02, comparison of 2 % and 5 % of damping

Sequence versus individual records

Although not visible from outside, the damage/cracking from the previous test may have an important influence on the response of the subsequent test, in particular in the case of the predominantly elastic response (Fig.7). Therefore the sequence of all three records was used in the analytical prediction.

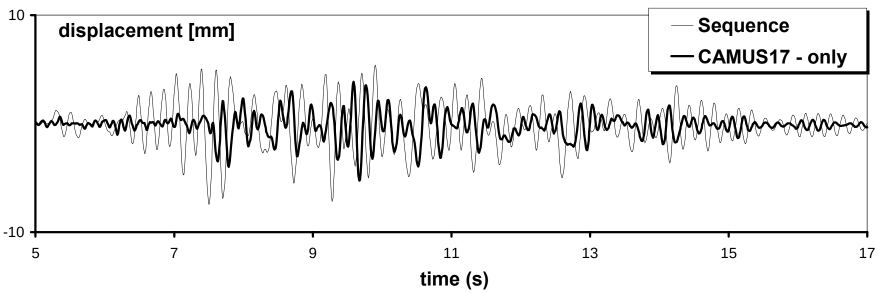

Figure 7. Displacement time-history, CAMUS17 sequence versus individual record

Parameters of the springs

Most of the parameters (e.g. yield force in the vertical springs) were determined from the first principles. However, hardening and unloading parameters had still to be chosen on the basis of the previous experience Elastic behaviour of shear springs was considered in the basic analysis. This was considered appropriate since the flexural behaviour of the lightly reinforced wall was expected. Some comparisons with the inelastic spring confirmed this expectation. It has been realised, however, that the shear cracking was not addressed in the model.

GENERAL CHARACTERISTICS OF THE PREDICTED BEHAVIOUR

The elastic strength of the analysed wall was high (it was concluded that no seismic force reduction was considered in the design and that some additional overstrength was provided by the choice of the reinforcement). Therefore, no yielding was observed in the response to Camus02 (cracking was quite intensive, however). Although Camus17 seemed stronger (higher maximum ground acceleration), it was actually the weakest signal in the high frequency range (see response spectrum). Therefore, no yielding was observed in the case of the response to Camus17, too. Only Camus19, having high maximum ground acceleration of 0.71g, was strong enough to cause considerable yielding of the wall.

Immediately after yielding, the non-redundant cantilever wall without mesh reinforcement became very weak and sensitive. The stability of the whole system depended strongly on the strain hardening parameter, which was difficult to estimate. It was predicted that only slightly stronger earthquake than CAMUS19 would cause the collapse of the wall (see next Section).

Since the wall capacity closely followed the demand over the entire height of the wall, the yielding was not confined to the base of the wall. Although this is not in accordance with the present Eurocode philosophy, it might be in accordance with the fact that no special construction details had been applied at the base of the wall.

MVLEM was able to identify considerable (permanent) uplift in the centre of the wall during the strong CAMUS19 excitation (Fig. 8).

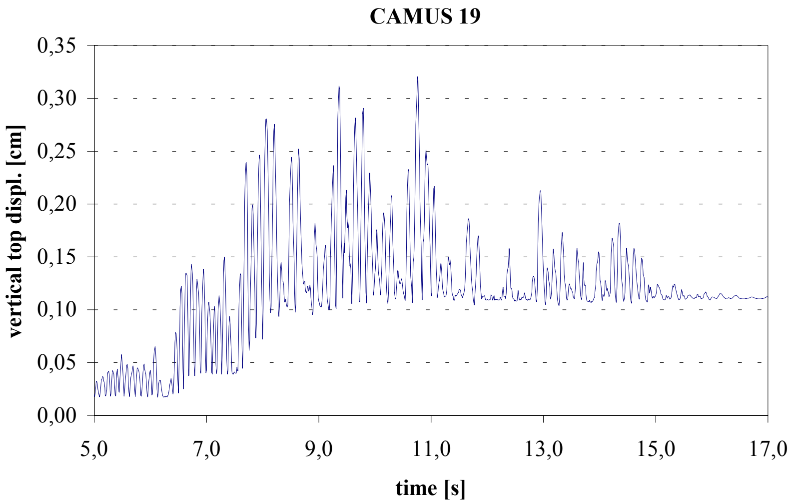

Figure 8. Uplift at the centre-line, CAMUS19

COMPARISON OF THE ANALYTICALY PREDICTED AND TEST RESULTS

In the case of the weak earthquake (CAMUS02) the prediction of the displacement time-history (Fig. 9) as well as of the hysteretic response (Fig.10) was very good. There was no yielding at this earthquake and cracking was obviously well modelled. The uncertainties in the initial pre-cracking stiffness had no major influence on the response.

Correlation for the strongest earthquake (CAMUS19) is good until the 11th second of the response (Fig. 11). The measured displacements are somewhat smaller than predicted. This might be the influence of inelastic shear or bond slip. In the 11th second something happened, that the model had not predicted. This was actually the failure of the wall, which had been analytically predicted for slightly stronger earthquake (see Fig. 12).

What came as a surprise, was an important influence of the uplift of the wall on the axial vertical force, which was of the same order as the axial force due to gravity. Although the model allows the calculation of the uplift (see previous Section), we had not paid attention to the vertical axial force and the masses in the vertical direction were not specified in the DRAIN-2D model. Additional preliminary analyses after the test have fortunately indicated that the influence of the fluctuating axial force might not be so important.

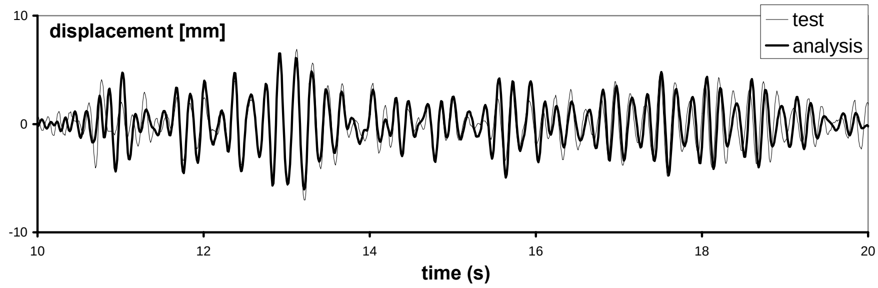

Figure 9. Displacement time-history, CAMUS02, test results versus analytical prediction

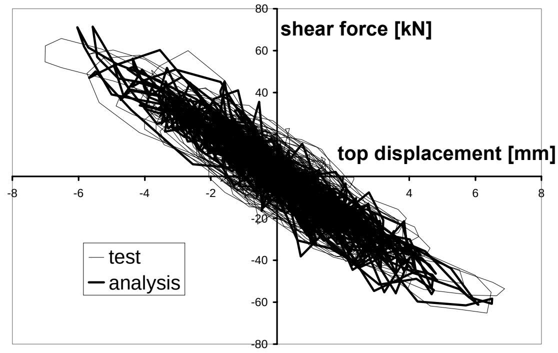

Figure 10. Top displacement – base shear relationship, CAMS02, test results versus analytical prediction

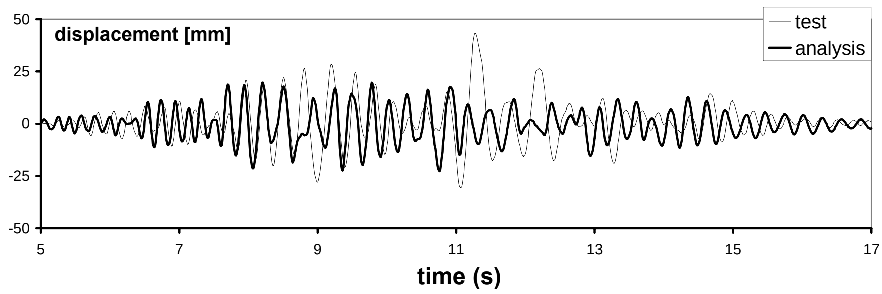

Figure 11. Displacement time-history, CAMUS19, test results versus analytical prediction

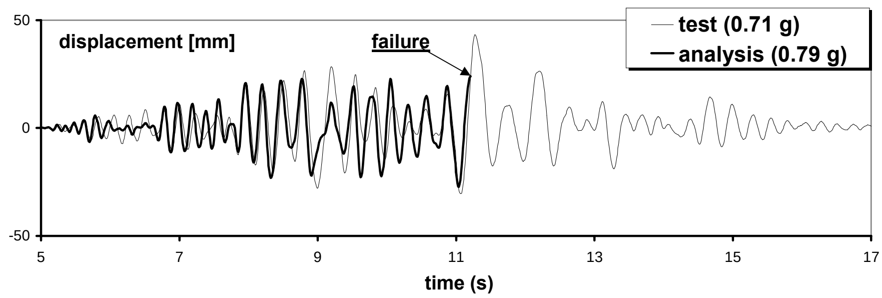

Figure 12. Failure prediction for slightly stronger earthquake (0.79g)

CONCLUSIONS

Non-redundant, lightly reinforced wall without mesh reinforcement was very sensitive after yielding. Analytical results were influenced by some parameters (e.g. initial stiffness, strain hardening, damping, and sequence of the test) which were difficult to choose in advance.

Nevertheless, relatively simple analytical tool, readily available to engineering community, was able to predict the response with acceptable accuracy in advance to the test (strength prediction was very good, failure estimation was close, yielding at upper stories was predicted). It is believed that (regarding all the uncertainties of the problem) further sophistication of the model may not substantially improve the results

Lessons regarding structural modelling include:

1. Viscous damping had an important influence on the response, in particular at lower levels of excitation. 2% of damping proved to be an appropriate value. The benchmark participants, using 5% of damping, grossly underestimated the response.

2. Initial damage of the test specimen as well as the damage from previous tests had an important influence on the time history response.

3. Inelastic shear deformations and pull-out of the reinforcement might had some influence on the response. However, due to several uncertainties, they were not considered in the final model.

4. A very important influence of the uplift of the cantilever wall on the vertical axial force was observed. This phenomena is still to be investigated.

Due to the very unstable response immediately after yielding of the wall the final conclusion is, that such design of structural walls should be used with great caution.

ACKNOWLEDGEMENTS

It was planned that our colleague Frano B. Damjanić would participate in the benchmark study. His early departure made this plan impossible. Without his rich experience and valuable contribution the value of the paper is significantly reduced. Nevertheless, we dare to dedicate this paper to his memory.

The contributions of Samo Križaj and Tomaž Vidic are gratefully acknowleged.

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