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Inelastic behaviour of reinforced concrete shear walls-energy approach

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ABSTRACT: Results of both the experimental and theoretical investigations on the reinforced concrete shear-wall behaviour under the quasi-dynamic loading actions have been presented in the paper. Experimental results have been compared with the performance of the analytical models. For the purpose of analysis, macroscopic modeling approach has been adopted, and Degrading Strength and Stiffness hysteretic model (DSSM) has been developed by the authors. In the comparative study, emphasis has been given to the energy and ductility indices, as well as to the energy response spectra.

1 INTRODUCTION

Shear-wall represent the basic load-bearing structural element for taking over the effects of earthquake and strong wind actions, both in the case of frame and panel structural systems. Modern concept of earthquake-resistant design is based on the premise of nonlinear behaviour of structures and their elements in the case of strong earthquake occurrence. That is why the nonlinear behaviour of shear-walls and their connections represents the subject of extensive experimental and theoretical investigations.

Previous investigations on this subject aimed at ameliorating the understanding of behaviour of shear-walls in the nonlinear range, as well as at recognizing their basic failure mechanisms. In addition, as the research results, quantitative data on the relevant indicators of the structural behaviour-ductility, ultimate strength etc. were obtained. Besides the above mentioned aims, research presented in the paper has been used for obtaining the functional relations between the different energy and ductility indices. The leading idea was to use experimentally obtained results for predicting the energy supply potential of the structure.

2 EXPERIMENTAL PROGRAM

In the IMS Institute, Belgrade, a series of reinforced concrete shear-wall models has been tested, featuring the welded connection utilized during the assembly phase of the structure. The model represented approximately 1/2 scale three storey high shear-wall prototype. This model series comprised three identical specimens having dimensions 400·200·15 cm (Petrović 1990).

In course of the experiment, models have been subjected to the alternate cyclic loading with "incremental reversed" loading regime. The model tip displacements as well as the load-cell force intensities were automatically registered during the experiment. Consequently, the sequence of hysteretic curves was obtained which forwarded the functional dependency force vs. displacement. The Figure 1 represents the force-displacement loading history for the first specimen. Experimentally obtained results served as a basis for formulating the analytical model of shear-wall behaviour under the quasi-dynamic and dynamic loading actions.

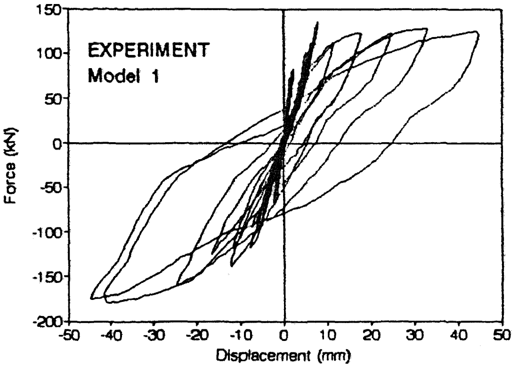

Figure 1. Force-displacement loading history specimen No.1

3 ANALYTICAL MODELS

Within the framework of this research, an attempt was made to simulate, as realistically as possible, the behaviour of reinforced concrete shear-walls with the dominant flexural influence subjected to the dynamic loading actions. Degrading Strength

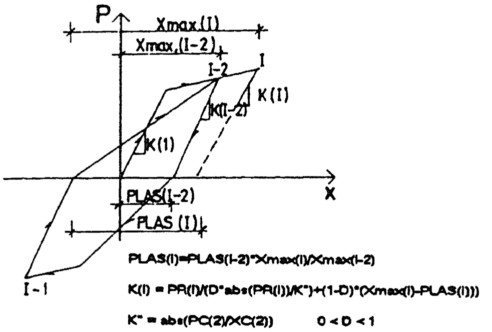

Figure 2. DSSM model-stiffness degradation rule

and Stiffness Model (DSSM) proposed by author of the paper (Nikolić-Brzev 1989) has some characteristics of the previously developed ones (i.e. Clough's and Takeda's), but at the same time represents a certain extension, having the possibility to describe the strength degradation upon reaching its ultimate value. Stiffness degradation is a function of the maximum attained displacement and the plastic excursion value. Detailed description of the model has been given elsewhere (Nikolić-Brzev 1989).

Upon analyzing the experimentally obtained force-displacement hysteretic loops (Figure 1), it has been concluded that skeleton line, obtained by connecting the points of peak displacements and corresponding forces for all cycles, may be well approximated by the four-branch polygonal line. The first branch corresponds to the elastic behaviour of the structure, the second is defined by the first crack appearance, the third by the yield-threshold of the reinforcement, and the fourth, decreasing branch, is defined by the process of deterioration of structure upon reaching the ultimate strength.

The DSSM also comprises the possibility of including the degradation of stiffness of the unloading branch, depending upon the maximal displacement XMAX(*i*) and the plastic excursion value PLAS(*i*) attained during the loading cycle *i*, as well as on the degradation index D, Figure 2.

Experimentally obtained results, especially force-displacement hysteretic loops (Figure 1), were compared with the analytical ones. In doing this, various hysteretic models were used, including the DSSM, bilinear and Clough's models. Force-displacement hysteretic loops, obtained analytically, are shown in the Figure 3. Besides the DSSM, Clough's and bilinear models were incorporated in the analysis. It is obvious that the DSSM simulates rather well the behaviour of the structure. Energy indices were used as the basic criteria for comparing performance of the different analytical models with the experimental ones.

4 THE ANALYSIS OF ENERGY INDICES

As is well known, ductility and ultimate strength represent the basic criteria in the process of earthquake-resistant design of structures. However, there is an alternative to this traditional approach which has been present for quite a some time. That is the energy concept of earthquake-resistant structural design, postulated by Housner, and recently elaborated by several authors (Uang 1988, Akiyama 1985).

Basis of the approach lies in the fact that the degree of damage caused to a structure during the earthquake depends, on one side, upon the energy which is being transferred to the structure in course of the earthquake excitation, and, on the other

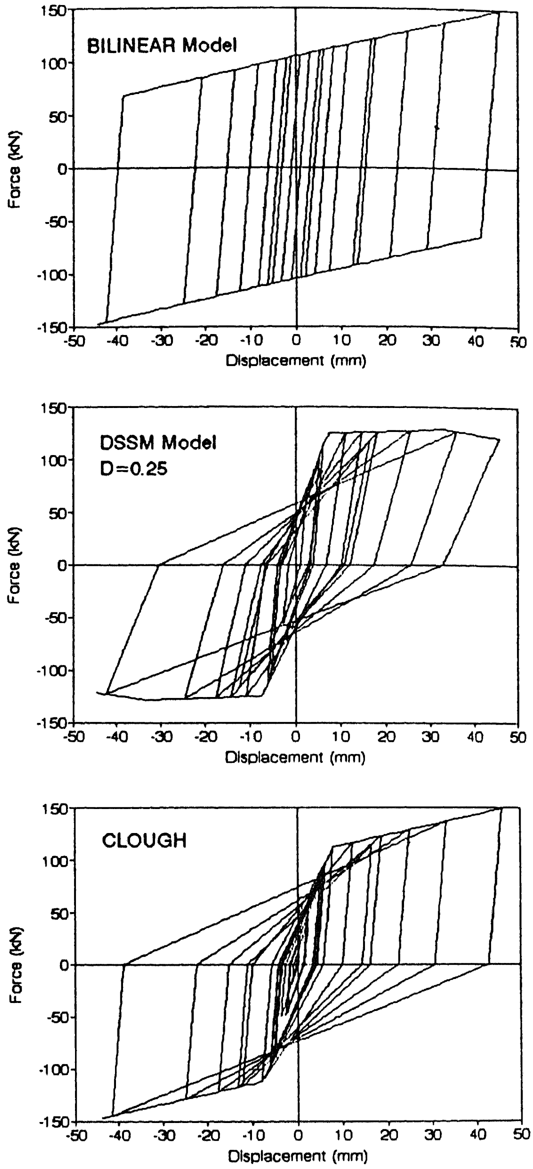

Figure 3. Force-displacement hysteretic loops for different analytical models

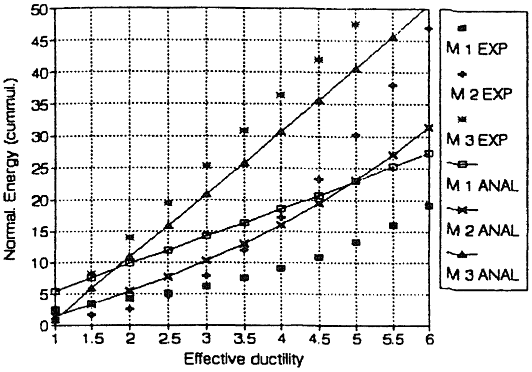

Figure 4. Effective ductility vs. normalized hysteretic energy ductility relations for analytical and experimental models

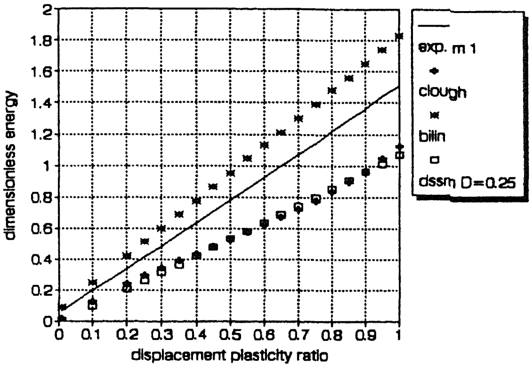

Figure 5. Dimensionless energy vs. displacement plasticity ratio relations for analytical and experimental models

side, upon its ability to absorb that energy. The energy which is transferred to the structure during an earthquake by way of seismic waves through foundations - input energy, is transformed into the following "component" energies. A part of this energy is being transformed into the recoverable elastic strain energy, the other part into the kinetic energy of vibrations of the structure, and the remaining part is absorbed by the inelastic displacements - irrecoverable hysteretic energy, as well as by the internal frictional effects in the structure - damping energy.

From the equations of dynamic equilibrium for single- or multi-degree-of-freedom-systems, the so-called "energy equations" can be derived (Uang 1988). Consequently, besides the commonly used ductility and acceleration response spectra, various energy-based response spectra (i.e. input energy, kinetic energy, damping energy and hysteretic energy spectra) can be easily worked out. In this way, the energy demand can be determined for a system with the given mechanical characteristics subjected to the earthquake-type excitation. On the other hand, based on experimental and analytical investigations, functional dependencies between the relevant energy indices and ductility factors for various structural elements can be determined. These data point out to the energy supply potential of the given structure. By comparing these two values - energy demand and energy supply, it can be concluded whether the structure is able to bear the influences of the expected earthquake excitation.

Force-displacement hysteretic loops, obtained by quasi-dynamic and dynamic testing of structures, can provide valuable informations on the quantity of energy dissipated by the system through inelastic deformations in the process of progressive cyclic loading. Dissipated energy can be well *correlated with the values of peak displacements* during the each half-cycle of loading. However, in order to generalize this relation, these indices can be normalized in adequate ways. One of normalized energy indices was suggested by Mahin (1983), who termed it normalized hysteretic energy ductility factor. This factor can be obtained by normalizing either total (cumulative) amount of energy dissipated by the system during all cycles or energy absorbed during the current loading cycle, by twice the energy absorbed at first yield, plus one. This index can be correlated with effective ductility factor, which represents the ratio of the maximum displacement during a half-cycle and the displacement at the threshold of yield.

In Figure 4, functional dependency between the normalized cumulative energy and effective ductility for the experimental models and the analytical hysteretic model DSSM is presented. Parameters of the DSSM (stiffness values of skeleton lines and D factor value) were determined from the experimentally obtained hysteretic loops, by applying the least square method. In all the cases, linear dependence exists between the normalized energy and ductility indices.

In addition to the mentioned indices, another important energy index is the dimensionless energy, *e*, which can be correlated with the displacement plasticity ratio P_d. Dimensionless energy *e* is equal to the dissipated energy during a single half-cycle of loading normalized by the elastic strain energy during the same period. Displacement plasticity ratio P_d is equal to the plastic excursion value for the single half-cycle of loading normalized by the maximum displacement reached during the same half-cycle. Plastic excursion value represents the residual inelastic displacement that remains in structure after unloading in each loading cycle. This functional relation for the experimental models, as well as for the analytical DSSM model, is presented in Figure 5.

Besides the energy indices, an important indicator of structural behaviour in nonlinear range is ductility. It is commonly expressed through the effective ductility factor, which is defined as a ratio of the maximum displacement (at the failure point) u_u and the displacement at the threshold of yield u_y. Effective ductility may be a good indicator of inelastic structural behaviour in the case of monotonic loading. However, in the case of cyclic

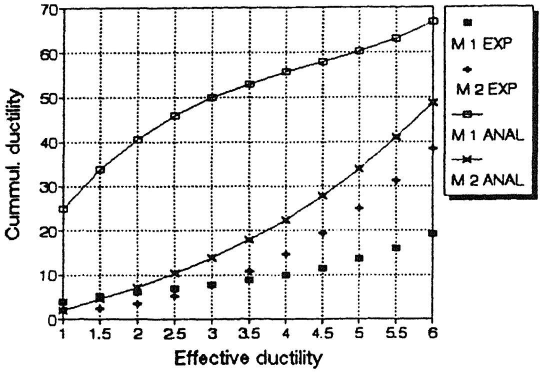

Figure 6. Effective ductility vs. cumulative ductility relations for analytical and experimental models

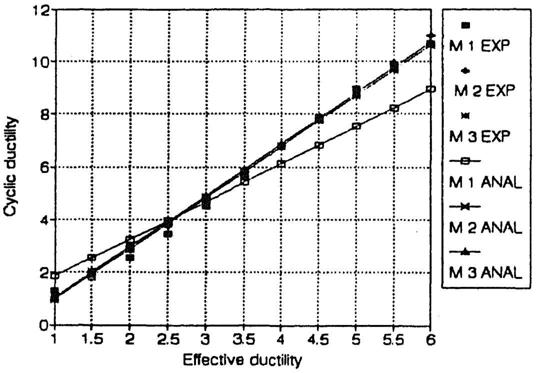

Figure 7. Effective ductility vs. cyclic ductility relations for analytical and experimental models

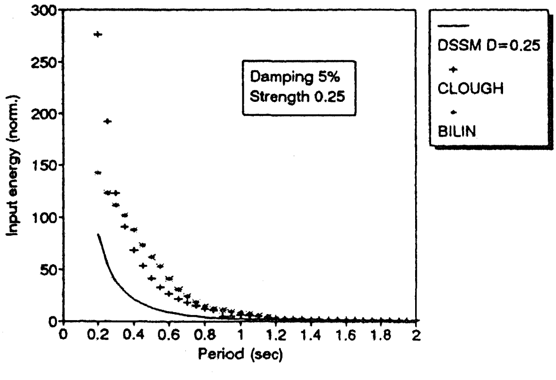

Figure 8. Input energy spectrum for various analytical models

loading, this factor cannot point out to real values of the inelastic deformations. Nevertheless, effective ductility factor still represents one of the basic criteria in the present earthquake-resistant design methodology, and that is why we found it natural to correlate its values with the other energy and ductility indices in the paper.

One of the relevant ductility indices is accumulative displacement ductility factor, especially for structures susceptible to low cycle fatigue failures. This factor is equal to the sum of all plastic excursions normalized by the value of displacement at the threshold of yield, plus one. Accumulative ductility defined in such a way differs from the formulation given by Mahin (1983), and it points out to the total amount of irreversible inelastic (i.e. plastic) deformation the system has experienced. Figure 6 shows functional dependence between effective and accumulative displacement ductility factors for the experimental models and the analytical model DSSM.

Another, also very important index, is the cyclic ductility factor, as defined by Mahin(1983). This indicator provides information on the maximum deformation attained during a cycle of loading, normalized by the displacement at the threshold of yield, and may be correlated with the effective ductility factor. Figure 7 shows that the cyclic ductility always exceeds effective ductility value, at least in the case of experimental models which are the subject of this research.

Above presented energy indices, obtained as a result of the experimental investigations, point out to the energy supply potential of the shear-wall structure under the quasi-dynamic loading actions. Based on these results, energy supply of such a structure under the expected earthquake can be predicted. From the other side, energy response spectra for any earthquake-type excitation can be worked out (Uang 1988).

Consequently, information on energy demand requirements for the structure with the given mechanical characteristics can be obtained. As an example, absolute input energy (Figure 8) and ductility response spectra (Figure 9) have been worked out for the 1979 Montenegro earthquake (hotel "Oliva", Petrovac acceleration record, PGA=0.45g, duration 14.0 sec.). Analyses have been carried out for the system having relative strength of 0.25 and viscous damping ratio of 5%. Relative strength of the system is defined here as the ratio between the system's yield strength and the peak ground acceleration (for the unit mass system). Different hysteretic models, i.e. DSSM (D=0.25), Clough's and bilinear models have been utilized in the analysis. By observing the presented spectra, it can be deduced that the DSSM model yields the most conservative results both for the energy and ductility spectra in the fundamental period range 0.2-1.0 sec.

5 CONCLUSIONS

From the above presented results, obtained from the research on the behaviour of RC shear-walls subjected to the quasi-dynamic loading actions, the following observations can be made.

1. Proposed analytical model (DSSM) is able to simulate rather realistically behaviour of the RC slender shear walls under the cyclic loading actions. This has been concluded upon carrying out

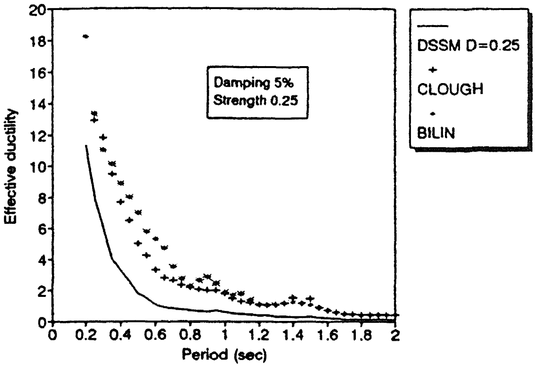

Figure 9. Ductility spectrum for various analytical models

comparative study on the performance of different analytical models and experimental specimens subjected to the quasi-dynamic loading actions.

2. Various energy and ductility indices obtained by processing of experimental data may provide valuable informations on the energy supply potential of the structure. However, for the sake of obtaining more reliable functional interrelations between the indices, it is necessary to carry out further experimental investigations.

3. Energy response spectra, obtained as a result of the direct dynamic analysis, provide informations on maximum values of the input energy to be transferred to the given structure during the earthquake excitation. These spectra have advantage over the commonly used ones (i.e. ductility and acceleration spectra) by including influences of the excitation duration and loading path in the response. From the other side, they have a disadvantage in the fact that they cannot be used in engineering practice in the simple way, as there is no sufficient data on the energy supply potential for the various types of structures.

ACKNOWLEDGMENTS

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