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Experimental research for the hysteretical behaviour of reinforced concrete wall system of special structural scheme

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ABSTRACT: The subject is definition of the hysteretical behaviour of a protruded reinforced concrete wall system fastened to a core under cyclic force. The strength, deformability and ductility of the wing part, consisted of monolith transverse walls, longitudinal walls with openings and floor slabs are studied. The scale of the model is 1:10, the length of the protruded wing part corresponds to a five fold span. Instrumentation and set up to the model, enabled to define capacity of strength and deformability at the yielding of reinforcement and the ultimate state. The test results of strength and deformability of the model have been compared with the analytical results. The research results showed that the supporting structure of the wing part of the Ryugyong Hotel building has considerable capacity of strength and deformability. The results have been used to evaluate the earthquake safety of the Ryugyong Hotel building and it will be of value to earthquake-proof designing of this type of buildings.

1. INTRODUCTION

Anticipated within the framework of the project "Experimental investigation of a 105-storey hotel building in Pyongyang, DPR Korea" were experimental investigations of models of the building structure under quasi-static cyclic loads that were to be designed, prepared and tested in the laboratory of IZIIS - Skopje.

Due to the complex building structure, both at plan and along the height, it was not possible to encompass all the characteristic forms of cross-sections of structural elements and characteristic assemblages in quasi-static testing of these models. Therefore, four types of structural assemblages that reflected the most vital bearing structural elements were selected and further designed as six-storey models in scale of 1:5 for quasi-static testing under cyclic horizontal loads. One model representing the central core of the building and part of one wing was designed in scale of 1:10.

Apart from the processing of the results obtained from testing of the models, performed were also analytical investigations of the mechanical characteristics of the models by applying the world-wide achievements in the field of earthquake engineering whereby it was possible to compare the experimental and analytical characteristics of the behaviour of the models.

Finally, conclusions were drawn regarding the behaviour of the models that were exposed to combined horizontal and vertical cyclic loads as to the strength and deformability capacity of the models as parts of the global structure of the building.

2. DESIGN OF MODEL "C"

Model "C" is designed for the purpose of determination of the bearing capacity and deformability of the connection between the central core and the wing of the building. Considering the fact that the structure of the core of this building is very complicated (Fig. 1) and consists of a large number of vertical walls of different forms in plan, model "C" is a simplified plan of the core of the building with approximately the same moment of inertia as that of the prototype in the selected scale of 1:10.

The structure of the wing is more regular so that the design of the model was made easier. In vertical direction, the model consists of three storeys with four floor slabs, which are grouped into two slabs (the top and the bottom slab) considering the possibilities regarding the elaboration of the model and the placement of the formwork inside the model (Fig. 2).

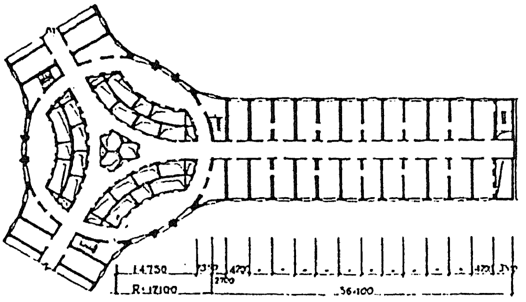

Figure 1. Plan of the core and wing

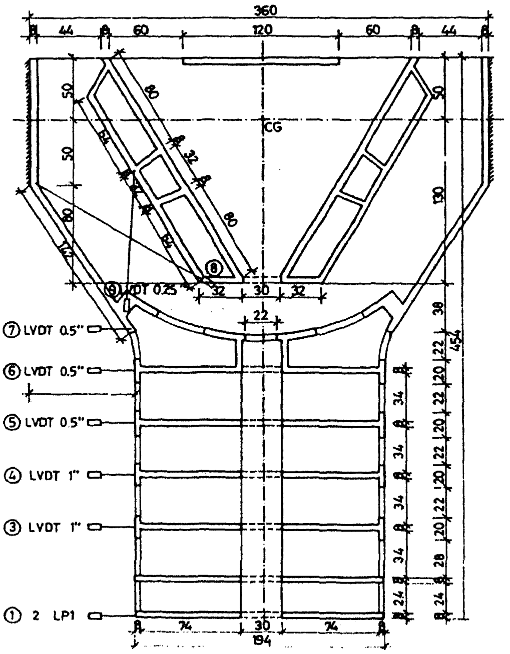

Figure 2. Plan of the model 1:10

The reinforcement of the model slabs is presented in Fig. 3 and consists of a reinforcement network in each slab. The amount of reinforcement is designed in accordance with the reinforcement of the prototype. Apart from the reinforcement of the slabs, there is also a vertical reinforcement in the walls of the model which is concentrated at some characteristic points of the plan. Along the walls, there is also a network of vertical and horizontal reinforcement bars (Fig. 3). A horizontal reinforcement between the window openings of the side walls of the wing is also designed.

Since the central core of the model is fixed at both side ends and the horizontal load is applied on the top of the wing, it is abvious that the bearing capacity of the model exposed to horizontal loads depends mainly on the reinforcement of the slabs that experiences tensile and compression stresses under cyclic loads applied at the end of the model wing.

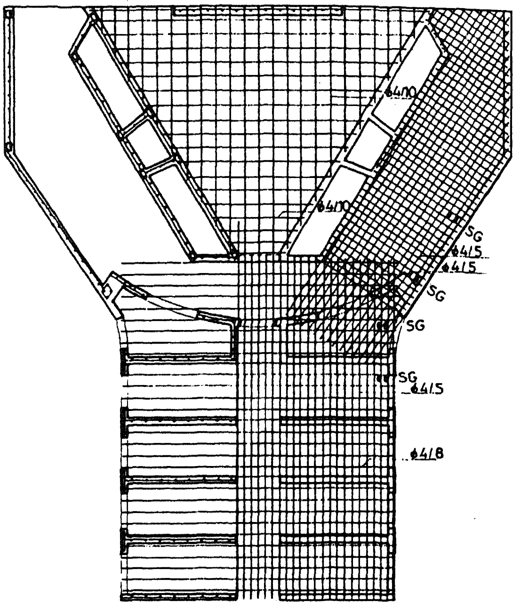

Figure 3. Reingorcement in slabs and walls

The uniformly distributed reinforcement of the critical cross-section of the slab that has an effective depth of 194 cm, is 0.63% in both directions which is a considerable amount in comparison with the reinforcement that is concentrated at the end of the critical cross-section.

As this model is loaded only by a single horizontal force via the side walls of the wing that can freely be deformed in horizontal direction, the external instrumentation of the model consists of a load cell, transducers for measurement of displacement placed in the direction of all the transverse walls of the wing and four transducers for measurement of the variation in length in the zone of the core (Fig. 2).

The internal instrumentation consists of strain gauges for measurement of strains in reinforcement which are placed at several places along the length of the model, from the fixation point towards the wing (Fig. 3).

Testing of the trial samples enabled to obtain the following data on the characteristics of the built-in concrete:

. Compressive strength of the prisms (3 prisms) = 27 MPa, i.e., 35 MPa for a cube proportioned 20 x 20 x 20 cm;

. Tensile strength due to bending - 3.4 MPa.

. Modulus of elasticity under pressure 24.000 MPa.

3. TESTING OF THE MODELS

Testing of the models under quasi-static horizontal and vertical cyclic loads was performed in the IZIIS laboratory in Skopje.

The equipment for quasi-static tests consists of supports, hydraulic actuators, connections between models and equipment and low speed data acquisition system. Testing of the models was performed in a horizontal position, by fixation in the steel supports via the foundation. The remaining part of the model was supported by movable bearings via parts of its floor slabs which enables free deformation of the model in its plane.

The intensity of the horizontal load was gradually increased during the test until it reached the characteristic values for the occurrence of the first cracks, the yielding of the tensiled reinforcement and the ultimate bearing capacity of the model.

3.1. Results from testing of model "C"

Model "C" that represents part of the central core and part of the wing of the building was tested under horizontal torsional effect, the theoretical support at the centre of gravity of the building being simulated via two supports at the ends of the core (Fig. 2).

The loading of the model was performed with a horizontal force applied at the end of the wing, the force being applied through steel profiles fixed to the side walls of the wing by bolts. The elements sustaining the horizontal force were the upper and the lower slab that behaved as walls in their plane and parts of the facade walls that acted as flanges in a double "T" cross-section. During the test, no axial force was applied on this bearing element.

The test results are presented via the hysteretic diagrams of horizontal force/ horizontal displacement of certain points of the wing of the model. Presented in Fig. 4 is the horizontal force - displacement at the top of the wing hysteretic diagram. The strength of the model at the occurrence of the first cracks, yielding and ultimate state are given in Table 1. The test results show a gradual increase in strength with the increase of the horizontal displacements. After reaching of the maximum strength, a local failure of the connection between the steel profiles for the transfer of force and the walls of the model took place which gave rise to an increased horizontal displacement at the top of the model (Fig. 4).

4. EVALUATION OF THE EXPERIMENTAL RESULTS

For the purpose of evaluation of the experimental results, the following aspects of the behaviour of the models were investigated: strength, displacement and ductility. Presented in this paper will be the analytical investigations of the strength and deformability of model "C" as well as the comparison between the analytical and the experimental results.

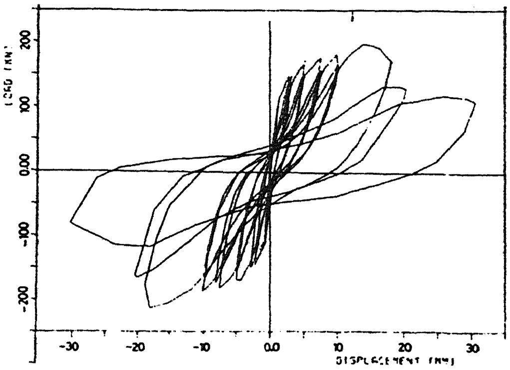

Figure 4. Shear force - displacement diagram for the tip of the wing

4.1. Strength of the tested models

The strength of the models was evaluated from the following characteristic phases of structural response:

- occurrence of the first cracks under bending;
- beginning of the yielding of the tensiled reinforcement;
- ultimate strength under bending effect;
- ultimate strength under shear effect.

4.1.1. Strength at the beginning of the yielding

The determination of strength at the yielding of reinforcement is very important as this state represents in fact the beginning of plastic behaviour of the models. Apart from the reinforcement concentrated at the ends of the reinforced concrete walls, there is also a uniformly distributed reinforcement along the cross-section length so that the yielding of the tensile reinforcement is not uniform. The yielding of reinforcement starts in the outermost bars, next to the tensile edge of the cross-section after which it expands to the remaining bars. The bars which are near the neutral axis do not experience yielding strains. When computing the yielding moment for the walls, it is adopted that yielding of the whole reinforcement concentrated at the edge of the cross-section takes place.

The factors that have a paramount influence upon the yielding strength are the amount and the quality of the reinforcement in the cross-section, the proportions of the cross-section and the strength of concrete as well as the amount of axial force in the cross-section.

For model "C", the analytical value of shear force at yielding is lower than the experimental one which is the result of the characteristic distribution of reinforcement in the slabs (nonuniform yielding of this reinforcement). The experimental value is determined from the shear force/horizontal displacement hysteretic diagram (Fig. 4).

4.1.2. Ultimate bending strength

When determining the ultimate bending strength, it should be taken into account that there are cracks and local failure of concrete in the models and there maybe even buckling of the main reinforcement in the slabs. The experimental values of ultimate strength are determined from the Q-Δ hysteretic diagrams where the shear force drops at the end of the test in comparison with the maximum shear force. The shear force should not drop from more than 20%.

For determination of the analytical value of the ultimate moment, the factors that have a paramount effect on the ultimate moment are the same as those that affect the yielding moment.

Apart from this, it has been adopted that the ultimate compression strain of concrete is 0.0035 which means that a nonconfined concrete was used for the cross-section of the walls.

The neutral axis depth is considered to be less than the overall depth. The compression steel, at the ultimate load, generally reaches the yield strength.

4.2. Deformations and displacements of the models

The horizontal displacements of the models were measured during the testing, while the analytical investigation of deformations and displacement were focused on the yielding and the ultimate states.

The horizontal displacement for the state of the occurrence of the first cracks (only the first storey), yielding of reinforcement and the ultimate state (for the first, the second and the sixth storey) were measured.

During the nonlinear range of behaviour of the models, the cracks are already formed and it is very difficult to estimate the deformation in the reinforced concrete elements. The nonlinear deformation of the walls are concentrated in the lower storey, the bending and the shear deformations being of equal importance. For the determination of the bending deformations it is necessary to compute the curvatures of the wall cross-section at the state of yielding of reinforcement and the ultimate state. For the computation of the ultimate bending deformations, it is necessary to know the hieght of the plastic zone of the wall. There are several empirical expressions for determination of the plastic zone. We decided to use the procedure developed by Hiraishi and Kawashima (1988).

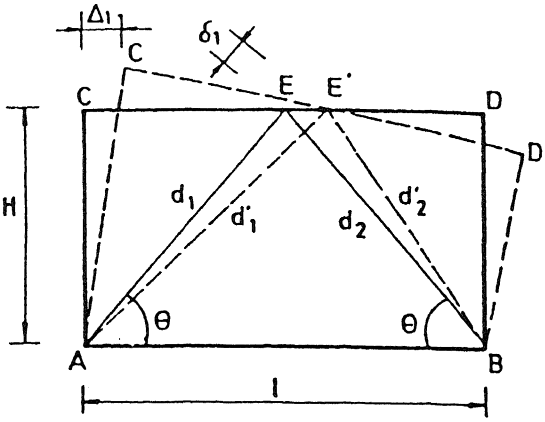

Figure 5. Deformation of the truss

4.2.1. Bending deformations at yielding

The bending deformations that occur at yielding state are computed on the basis of the computed curvatures at yielding, the diagrams of the curvatures along the height of the walls being identical with the diagrams of the moments from the elastic analysis of the models. The diagram of the curvatures at yielding state makes possible to compute the rotation angles for each storey of the models, the sum of the areas of the curvature diagram representing the rotation angle of each storey along the height of the wall. The total horizontal displacement at each storey can be computed by forming a static moment from the areas of the curvature diagram, successively from the first to the top of the models. The relative storey displacements for each storey are obtained from the total horizontal displacements.

4.2.2. Shear deformations at yielding

The truss analogy is used for computation of shear deformations. The vertical reinforcement in the walls, concentrated at the ends, represents the top and bottom chord of the truss. The reinforcement in the floor structure represents the vertical of the truss while the diagonals of the truss are represented by the equivalent width of the compressed concrete and the tensiled diagonal of the reinforcement in the panel (Simeonov, 1984), Fig. 5.

In the case of walls with diagonal cracks, most of the horizontal load is sustained by the compressed diagonal and the horizontal reinforcement in the web of the wall. Taking this into account, the expression for the shear angle for the first storey can be derived from the equivalent truss.

$$\gamma_{av} = \frac{Q.1}{4Asp.Es.H} + \frac{Q.d_1.d_2}{b.Be.Ec.\cos\theta} \cdot \frac{1}{H.1}$$

The horizontal shear displacement for the first storey is equal to:

$$\Delta_{1ms} = \gamma_{av}.H$$

$$\Delta^{y}_{1,s} = \frac{Q.1}{4Asp.Ea} + \frac{Q.d_1^2}{b.Be.Ec} \cdot \frac{1}{\cos\theta.1}$$

where,

Q - shear force at yielding;
Asp - reinforcement area in the floor slab;
Es - elasticity modulus of reinforcement;
Ec - elasticity modulus of concrete;
Be - effective width of the compressed diagonal Be = 0.2.1 cos0;
b - thickness of the wall rib;
1,H - length and height of the wall;
d_1, d_2 - diagonal of the wall

4.2.3. Ultimate deformations and displacement

The ultimate deformability capacity of multistorey walls is one of the most important factors for the seismic behaviour of reinforced concrete mixed structures consisting of frames and walls. The analysis of these walls after yielding due to bending proves that the hypothesis about the distribution of the curvature being equal to that of the moments cannot be adopted. A new model of a truss consisting of a non-prismatic concrete element and rigid elements is therefore proposed. The test results show that there is a stable area of deformations where the deformed profile along the height of the wall does not change after yielding due to bending. In this stable area, the displacement angle, Ri, at each storey is equal to the rotation angle immediately over the plastic zone of the wall (Oesterle, Fiorato, Aristizabal-Ochoa, Corley - 1980).

The stretching of the non-prismatic element along its height is determined from the stresses in tensiled reinforcement and on the basis of equilibrium of forces along the diagonal cracks. The equilibrium of forces is presented in Fig. 6 with the assumption that the whole longitudinal and transverse reinforcement along the radial cracks yields or approaches the yielding point.

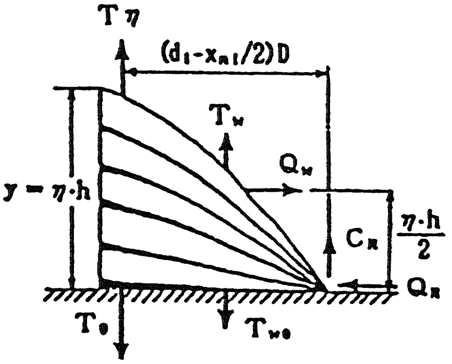

Figure 6. Simplified equilibrium on a crack surface

If a slightly increased shear force ΔQ is applied on panel ABCD (Fig. 5), after yielding of the first storey due to bending, the following displacements take place in the equivalent truss:

1. The AC chord is considerably elongated due to yielding of the longitudinal reinforcement;

2. The BD chord is not notably shortened since the concrete sustains the compression stresses;

3. The main elements of the shear mechanism are the longitudinal elements of the equivalent truss, the transversal ones and the compressed diagonal. The tensiled diagonal practically does not have an axial tension rigidity after the occurrence of the diagonal cracks.

The elongation of the AC chord due to the yielding of the longitudinal reinforcement depends on the elasticity modulus, E_{sh}, and the length at which yielding od reinforcement takes place which is equal to the height of the plastic zone.

Considering the geometry of the equivalent truss, the expression for the shear angle of the first storey was derived and hence the horizontal shear displacement at the first storey which is as follows:

$$\Delta^{u}_{1,s} = \left[\frac{y}{2A_s.E_{sh}.H_1} + \frac{1}{2A_c.E_c} \right] \cdot \frac{\Delta Q H_1^3}{1^2} +$$

$$+ \left[\frac{\Delta Q.1}{8A_{sp}.E_s} + \frac{\Delta Q d_1^2}{b.B_e.E_c} \cdot \frac{1}{\cos\theta.1} \right] + \Delta^{y}_{1,s}$$

where all the indications are the same as those described before, except for the new ones:

A_s - area of the tensiled reinforcement at the end of the wall;
A_c - total area of the concrete cross section.

Table 1.

Q_{cr}^{T} (kN)	Q_{cr}^{A} (kN)	Q_{y}^{T} (kN)	Q_{y}^{A} (kN)	Q_{u}^{T} (kN)	Q_{u}^{A} (kN)
100.0	65.0	150.0	105.0	194.0	200.0

Table 2.

Δ_{y}^{T} (mm)	Δ_{u}^{A} (mm)	Δ_{u}^{T} (mm)	Δ_{u}^{A} (mm)	D_{Δ}^{T}	D_{Δ}^{A}
3.14	4.23	16.22	18.10	5.17	4.28

5. CONCLUSIONS

Results from this investigation showed that the supporting structure of the wing part of the Ryugyong Hotel building has considerable capacity of strength and ductility.

The test results were compared with the analytical ones, obtained by theory of ultimate strength capacity of reinforced concrete section and elements and showed good correlation. These results have been used to evaluate the earthquake safety of Ryugyong Hotel building.

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