17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Dynamic Response of LPRCS Subjected to Long-lasting Ground Motions, Basis of Experimental Investigation of Joints and Multistory Models

Zh. Lj. Bozhinovksi[(1)], D. Dojcinovski[(2)], A. Zlateski[(3)], E. Delova[(4)], M. Poposka[(5)]

[(1)] *Professor, PhD, UKIM-IZIIS, Skopje, R. N. Macedonia, zivko@iziis.ukim.edu.mk*
[(2)] *Professor, PhD, UKIM-IZIIS, Skopje, R. N. Macedonia, dragi@iziis.ukim.edu.mk*
[(3)] *Ass. Researcher, M.Sc., UKIM-IZIIS, Skopje, R.N. Macedonia, azlate@iziis.ukim.edu.mk*
[(4)] *Ass. Researcher, M.Sc., UKIM-IZIIS, Skopje, R. N. Macedonia, delova@iziis.ukim.edu.mk*
[(5)] *Ass. Researcher, M.Sc., UKIM-IZIIS, Skopje, R. N. Macedonia, marina@iziis.ukim.edu.mk*

Abstract

Aseismic design of stable and economic structures is a complex process consisting of knowledge of the behavior of structures under static loads up to failure, as well as, the dynamic response of the structures under real seismic loads.

There is a particular problem when certain damages occurs in a structure exposed on seismic impacts after the main shock which is followed with quite strong aftershocks.

For this purpose, each structural element like vertical panels, horizontal panels, vertical and horizontal joints participates in the structural response. The strength and stiffness of each element is changed upon reaching the elastic range of behavior at each step according to the global storey displacement. After reaching the yielding point, the stiffness continuously deteriorates down to the condition of dry friction among the structural elements. Complex analytical and experimental investigations of the behavior of the structural elements, the joints among them and multi-storey models using quasi-static and shaking table tests are necessary to confirm the stability and vulnerability of a specific large panel RC structural system.

Based on analytical and experimental investigations of large panel systems in our country and throughout the world, as well as, the investigations that are carried out for this purpose at IZIIS, procedure for design and analysis of stable and economic prefabricated large panel RC systems exposed to static and dynamic loads is proposed. With the proposed procedure, the vertical panels, vertical and horizontal joints with their behavior in linear and nonlinear range are included in the structural response but with controlled ductile behavior, up to ultimate and serviceability limit state.

Within the frameworks of the procedure, the results of the experimental investigations have provided the safest way of definition of strength, stiffness and deformability capacity as well as seismic energy dissipation ability, i.e., prediction of the behavior of bearing structural systems exposed to gravity and seismically-repeated cyclic loads.

In order to define the behavior of large panel systems, analytical and experimental research done on RAD – Belgrade large panel system will be presented.

The experimental investigations involve quasi static tests on joints, two storey and three storey 2D models and a model on a shaking table. These were further used to define the dynamic response of a real structure exposed to gravity and external seismic impacts.

In this paper will be presented the structural dynamic response to long-lasting earthquakes whereat, in the specific case, the records of the main shock and aftershock recorded on the same location have been used as an input accelerograms.

Keywords: aseismic design; economic LPRCS structure; strength; stiffness; analytical; experimental; dynamic response; long-lasting ground motion;

1. Introduction

The development of software for structural analysis, production and assembly technology enables design and construction of prefabricated large panel RC structural systems in seismic prone regions.

Their massive structure increases the seismic risk, so that design and construction errors might induce heavy consequences during strong earthquakes. The massive structure of LP systems initiates the need of designing stable and economical large-panel reinforced-concrete systems for construction in seismic prone regions, with defined ductile behavior of constituent elements and the whole structural system.

Prefabricated large panel RC systems depends on the behavior of their constituent elements - vertical wall panels, horizontal panel slabs, vertical and horizontal connections. So far, during the design and analysis of large panel systems under static and dynamic loads, the vertical wall panels have been considered to behave in elastic range. They are designed with identical dimensions and reinforcement distributed along the height of the building. They are reinforced with relatively high percentage of vertical and horizontal reinforcement, often with a non-controlled mechanism of behavior up to ultimate states of strength and deformability. Vertical and horizontal joints are considered to behave in the nonlinear range, as most of the total energy is being dissipated through them. After the occurred earthquakes, cracks and damages in the vertical wall panels have been observed which means that there are nonlinear deformations and damages due to the complex stresses induced by moderate and strong earthquakes. Diagonal cracks have not been observed. The same has been proved by the results of experimental investigations of fragments of large panel systems.

Based on the results from analytical and experimental investigations of large panel systems elements, a procedure for design and analysis of stable and economic prefabricated LP RC systems exposed to static and dynamic effects is proposed. With the proposed procedure, the panels and joints with their behavior in linear and nonlinear range are included in the structural response but with controlled mechanism of ductile behavior, up to ultimate states of strength and deformability.

To define the dynamic structural response, merged main earthquake and aftershock record as an input was used. The accelerograms were recorded at the same location - station Nocera Umbra, direction north – south, main shock and aftershock of the earthquake Umrbo Marchigiano.

2. Experimental investigations

Lately, efforts have been focused on analysis and design of stable and economic large-panel reinforced-concrete systems to be constructed in seismically active regions. Within the frameworks of the analytical procedure for analysis and design of stable and economical large-panel reinforced-concrete systems, the results of the experimental investigations represent the safest basis for definition of the strength, stiffness and deformability parameters and the seismic energy dissipation capacity, the variation in strength and stiffness under seismic effects of different intensity and frequency content as well as the mechanism of behavior of the elements and the system as a whole. The defined and verified parameters and behavior mechanisms of the constituent elements are used in definition of the mathematical models for prediction of the nonlinear behavior of structures under earthquakes.

Experimental and analytical investigations of elements and fragments of large-panel systems have been performed at IZIIS. Investigations objective is definition of strength and deformability characteristics, as well as, mechanism of behavior of models up to failure in order to define strength and deformability characteristics of actual structures.

2.1 JOINT DEFINITION – vertical joints of vertical panels

Vertical joint of vertical panels is in fact a cast in place joint of transverse and longitudinal wall panels. This is a closed joint, i.e., the surfaces of the precast elements enclose an area which is filled with concrete. A detail of the joint and the obtained hysteretic relationship between strength and deformability are shown in Fig. 1.

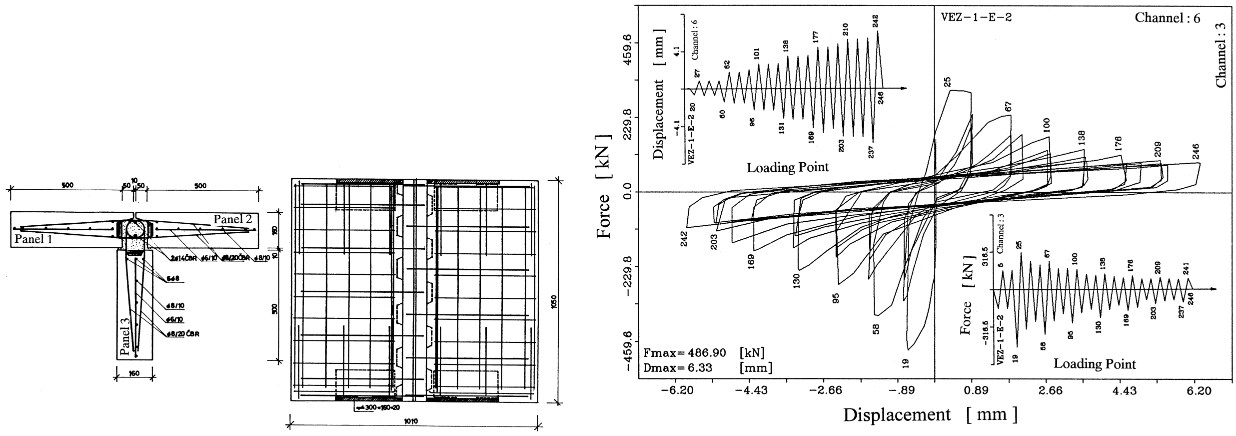

Fig. 1 – Detail and Hysteretic relationship P - δ, Model VEZ-1-EL-2, model in scale of 1:1

The main characteristic of behavior of vertical joints is high bearing capacity in the first phase up to beginning of occurrence of large inelastic deformations. With the increase in the intensity of the cyclic loading, an abrupt deterioration of stiffness and strength takes place, inversely proportional to the size of inelastic deformations.

2.2 Experimental investigations of three-storey models in scale of 1:3

Experimental investigations of three three-storey models of walls scaled 1:3 have been performed. The programme involves three characteristic panels: a solid rectangular panel with a vertical joint at the ends, a panel with an opening in the middle and a panel with walls in the opposite orthogonal direction - the so called wall with flanges.

PZM-1 - model of solid walls with rectangular cross-section, with horizontal and vertical joints. The characteristics for the model are shown in Fig. 2.

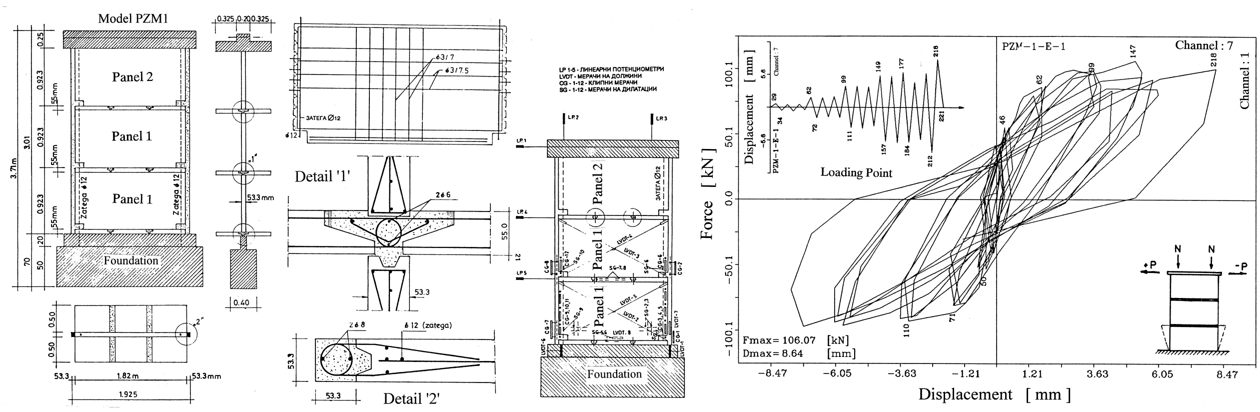

Fig. 2 - Detail and Hysteretic relationship P - δ, model PZM1-E-1, model to a scale of 1:3, first storey

On the basis of the results obtained from the experimental investigations, through evaluation of bearing capacity and deformability, the failure mechanism and hysteretic behavior, it may be concluded that prefabricated elements - panels are ductile elements of the structural system that are capable of absorbing energy which is evident from the shape of the hysteretic loop. The specific characteristics of behavior of the panel systems in nonlinear range manifested by a characteristic failure mechanism of opening of cracks along the contact zone, sliding, etc., are also present in this case but are not so pronounced. By introducing of anchors in the panels as a structural element, part of the panel and the vertical joint become activated in transferring of the forces which contributes to the decrease of the effect of opening of cracks. The introducing of the cast-in-place dowel at the ends of the panel contributes to the decrease of sliding along the contact surface so that the elements behave in a similar way as the cast-in-place walls.

2.2 Experimental investigations of two-storey models in model scale of 1:2

The main objective of the experimental investigations is definition of the main strength and deformability characteristics of the vertical wall panels and verification of their ductile mechanism of behavior.

The programme of experimental investigations involves four fragments of a large panel structure for the purpose of definition of their mechanical and deformability characteristics that will enable definition of the strength and deformability characteristics of the structure The models are constructed as two-storey models for the purpose of simulating the corresponding model and shear force in the lower panel. The precast elements for all the models were constructed at a construction site, based on a previously elaborated project, with reinforcement and shape of precast elements. The models consist of two vertical wall panels Panel 1 and Panel 2, two horizontal joints of vertical panels and a foundation. The panels do not represent elements of an existing large-panel system. Panel 1 - A and Panel 1 – B are flat and solid, without openings and flanges. Panel 2-A and Panel 2-B are identical to Panel 1-A and Panel 1-B, the only difference being that in the upper part they end with a beam, which is disrupted in the middle and serves for application of gravity and cyclic loads.

Model FKPZ-M-1 represents a two-storey wall consisting of two vertical panels, two horizontal joints and a foundation. The model is loaded with axial force, which simulates a wall with 8 storeys above the fragment (Fig. 3). A programme of full cyclic loading is carried out and force-displacement hysteretic relationships are obtained for different points of the model. One of the obtained hysteretic relationships is presented in Fig. 4.

Model FKPZ-M-2 is the same as FKPZ-M-1 but the axial force is simulating a wall with 4 storeys above the fragment. Figure 3 shows the shape of cracks after termination of the tests of model FKPZ-M-1and FKPZ-M-2. A programme of combined impulse and full cyclic loading is performed and force-displacement hysteretic relationships are obtained. One of the hysteretic relationships is shown in Fig. 4.

Similar to the previous two models, model FKPZ-M-3 also represents a two-storey model. The model is loaded with an axial force which simulates a wall with 4 storeys above the fragment (Fig. 5).

Presented in Fig. 6 are shapes of cracks after termination of tests of models FKPZ-M-3 and 4. A programme of full cyclic loading is carried out. One of the obtained force - displacement hysteretic relationships is shown in Fig. 7.

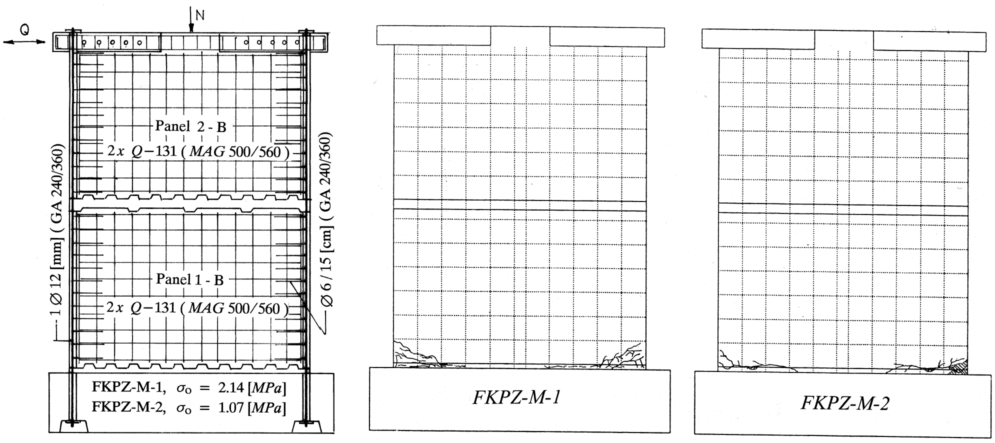

Fig. 3 - Detail and Shape of cracks of FKPZ1 and FKPZ2, model to a scale of 1:2

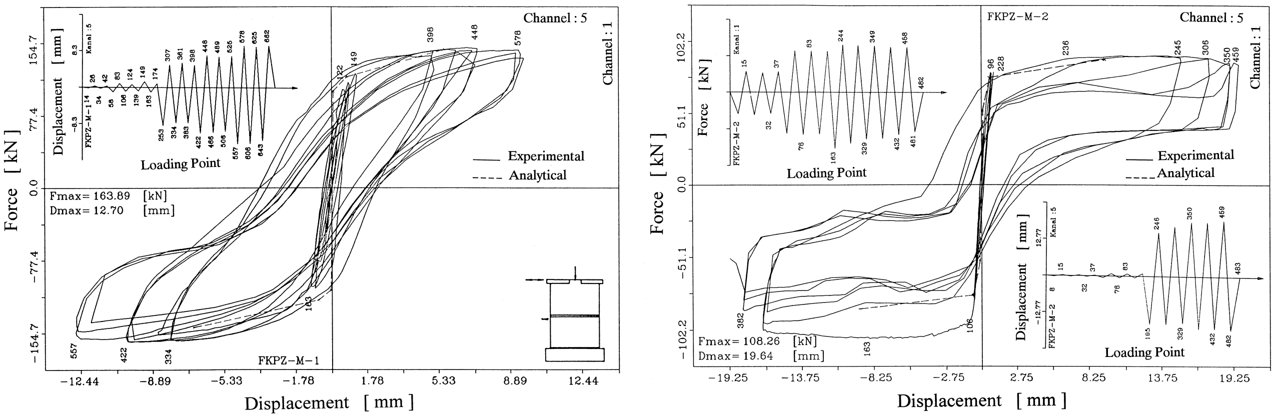

Fig. 4 - Hysteretic relationship P - δ, model FKPZ-M-1 and model FKPZ-M-2

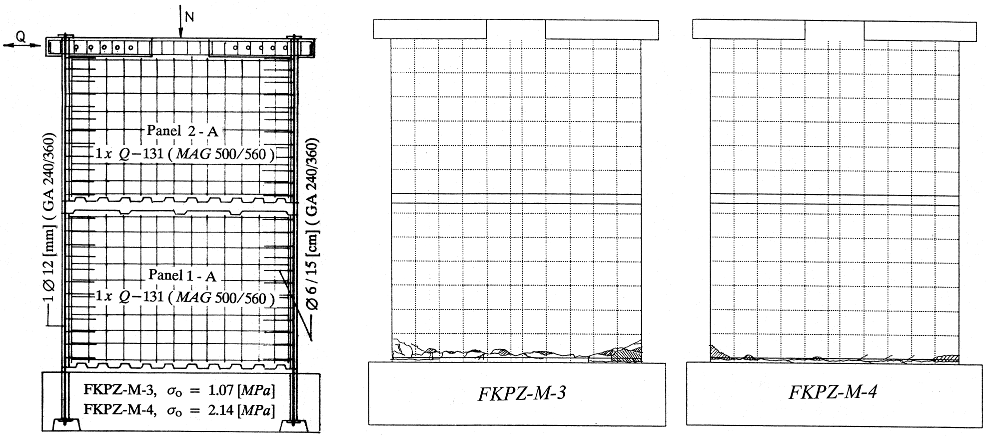

Fig. 5 - Detail and Shape of cracks of FKPZ-M-3 and FKPZ-M-4, model to a scale of 1:2

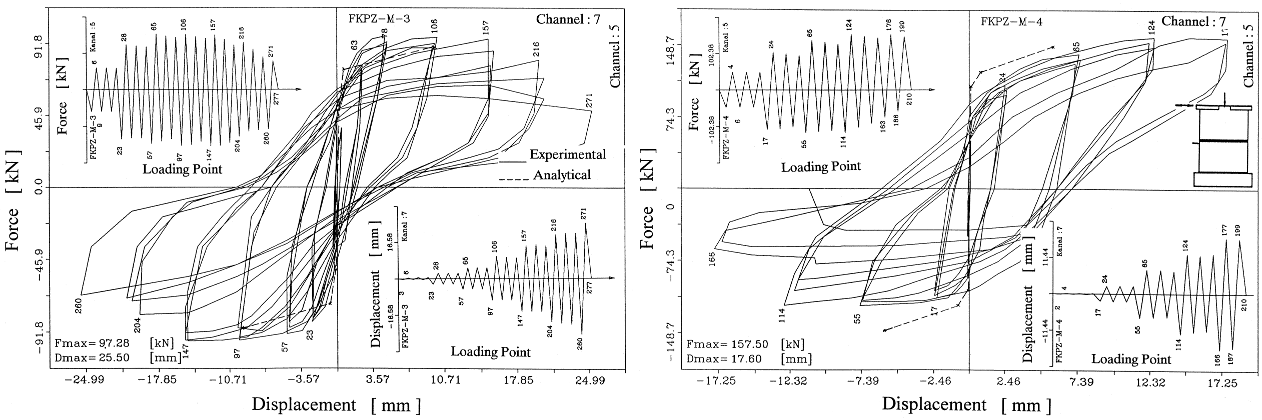

Fig. 6 - Hysteretic relationship P - δ, model FKPZ-M-3 and model FKPZ-M-4

The behavior mechanism of all the four models is similar. The main characteristics of behavior of the model is a ductile mechanism of behavior of the vertical wall panels. The model is characterized by a moderate strength and stiffness as well as a high deformability capacity, i.e., ductility, without diagonal cracks in the vertical wall panels and without sliding along the contact surface of the panels along the horizontal joints.

3. Analitical Investigations

On the basis of the synthesis of the results from the analytical and experimental investigations of elements of large panel systems performed in the world and in our country, and the investigations that are carried out for this purpose in IZIIS-Skopje, a procedure is proposed for design and analysis of stable and economic prefabricated large panel reinforced concrete systems exposed to static and dynamic effects (Fig 8). With the proposed procedure, the vertical panels are considered to behave in the nonlinear range, but with a controlled mechanism of ductile behavior, adequate reinforcement at their ends and several times smaller amount of vertical and horizontal reinforcement than that used in practice so far.

The procedure implies usage of experimental and analytical methods for determination of the necessary parameters. For a given system, minimal experimental investigations of constituent elements are necessary for development and verification of the system which is an accustomed practice and an obligation of the Producer. The procedure is further on analytical, in correlation with the experimental results.

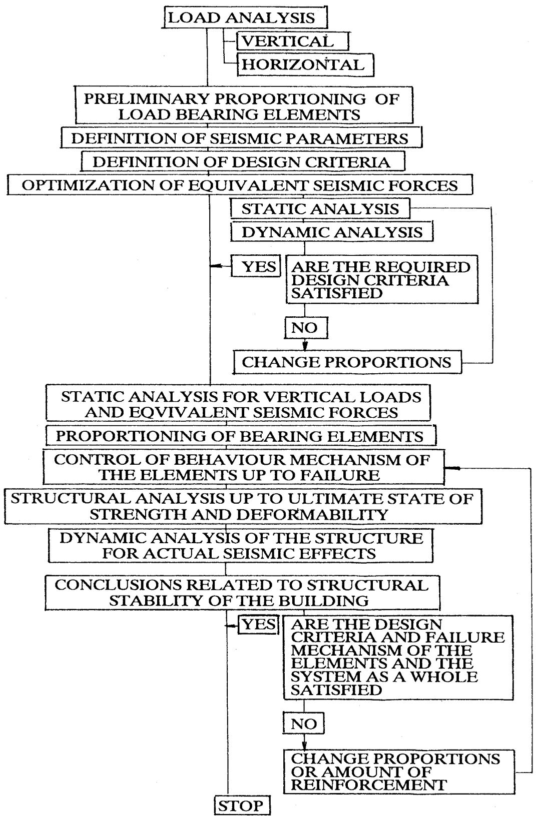

Fig. 8 - Flow chart for the analytical procedure

The proposed analytical-experimental procedure makes possible to develop, analyze and design large panel buildings to be constructed in seismically active regions. This practically means that development of a certain large panel system requires definition of the floor structure, the vertical wall panels, vertical and horizontal joints. The characteristics of the constituent elements, their interaction and the mechanism of behavior up to failure are experimentally verified. On the basis of the experimentally obtained characteristics and using the analytical methods, analysis and design of the considered large panel structures is carried out. The ductile behavior of the elements is controlled and the stability and the level of damage to the panels and the connection system is verified for the expected seismic effects at the site where the considered structure is to be built.

3.1 Design of elements

The nonlinear behavior of elements of large panel systems exposed to vertical - static and horizontal - dynamic loads, depends on the proportions of the elements, their distribution in the structure, reinforcement and their connection into a whole. To provide ductile behavior of the elements and the system as a whole, it is necessary that all parameters affecting their behavior be considered in the computations.

Identified parameters that affect the bearing capacity and the deformability of the bearing elements of large panel reinforced-concrete prefabricated systems are included in the models, the methods and the programme for analysis of the ultimate states of strength and deformability of bearing elements loaded with gravity - vertical and seismic - horizontal loads, from initial loading up to failure.

Designing of the structural elements is performed according to the ultimate limit state and serviceability limit state.

For vertical wall panels with defined geometry, reinforcement at the ends and uniformly distributed vertical and horizontal reinforcement, for a wall position in the structure with defined normal stresses, the mechanism of behavior is controlled up to ultimate states of strength and deformability in order to check their ductile behavior.

Ductile behavior of vertical wall panels implies the following order of the element behavior from the beginning of the loading up to failure (Fig. 9)

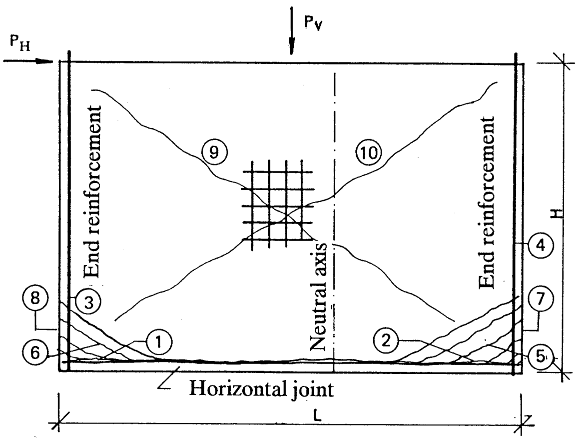

Fig. 9 - Ductile mechanism of behavior of panels

First, cracks occur in the tensile part of the concrete cross-section; the tensile reinforcement reaches the characteristic elastic limit; the compressive reinforcement reaches the characteristic elastic limit; crushing of concrete at the ends takes place on a relatively small area; reaching of ultimate strains in concrete, in the compressive part of the cross-section; and finally, occurrence of diagonal cracks due to main shear compressive and tensile stresses.

The diagonal cracks due to main shear compressive or tensile stresses may occur also prior to reaching of the ultimate strains in the compressive part of the concrete cross-section, for a lesser deformation than the required one and expected earthquakes of different intensity and frequency content, but never prior to reaching of the characteristic elastic limit in the reinforcement at the ends.

If certain elements exert a non-ductile behavior, modification of the reinforcement proportions is performed. If a ductile behavior cannot be provided by modification of reinforcement or the modification of proportions is not allowed by architectonic and other requirements, it is necessary to exclude the corresponding line of elements by their isolation from the bearing structural system.

The proportioning is performed according to ultimate states and hence there is a possibility to design elements with controlled ductile behavior.

The developed computer programme can also be used to evaluate the seismic resistance level of existing structures, by comparison of the strength and deformability capacity with the required maximum values according to technical regulations and expected seismic effects at the considered sites, with consideration of intensity and frequency content.–

3.2 Nonlinear dynamic response

The nonlinear dynamic response of structures exposed to gravity and seismic loads is of special interest, especially for the construction of buildings in seismically active regions. Based on the analysis of the experimental results, for elements loaded with cyclic loads, the shape of hysteretic force - displacement relationships, the mechanism of behavior from the beginning of the loading up to failure and damage of elements, a computer programme NALPS has been developed. For defining the nonlinear dynamic behavior of prefabricated systems under actual seismic effects, including the vertical wall panels, the vertical and horizontal joints with their strength and deformability characteristics.

For the strength-deformability relationships, polygonal diagrams for the vertical wall panels, vertical and horizontal joints are proposed, by which strength, rigidity and deformability under cyclic loads can be included in the model.

With the proposed polygonal diagram, one can apply the effect of initial rigidity, the effect of stiffness deterioration depending on the deformations and the number of cycles, the effect of stiffness and deformability in the course of the reverse cyclic loading, and finally, the sliding effect at each loading cycle. (Fig. 10)

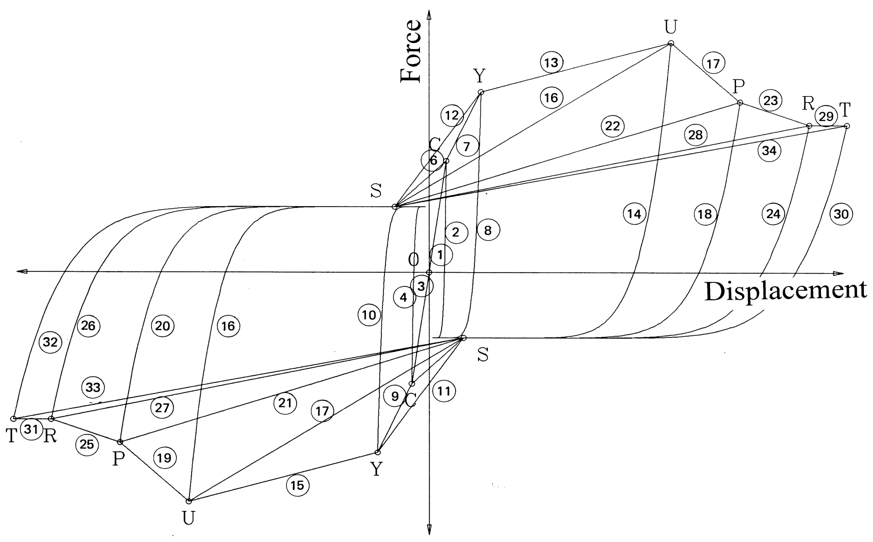

Fig. 10 - “BOZINOVSKI” hysteretic model P - δ

Through the polygonal strength - deformability diagram, the proposed mathematical relationship gives the possibility to include all the phases of the mechanism of behavior during the formation and the opening of the cracks, yielding of the principal reinforcement, crushing of the concrete in the compressed part of the joint along with much or less sliding along the length of the horizontal or vertical joints up to complete failure mechanism. In this way, included in definition of the dynamic response of the structure are the vertical walls panels, the vertical and horizontal joints, i.e., all the elements along the height of the building influencing the behavior of the structure as a whole. With such a mathematical model and computer programme, it is possible to define the response of the model of the large panel structure under expected seismic effect of different intensity and frequency content.

3.3 Analysis of characteristic large panel structures

In order to demonstrate the benefits from the proposed procedure, a detail nonlinear dynamic analysis has been performed on the three-story large panel structure. Figure 11 shows the layout of the selected structure.

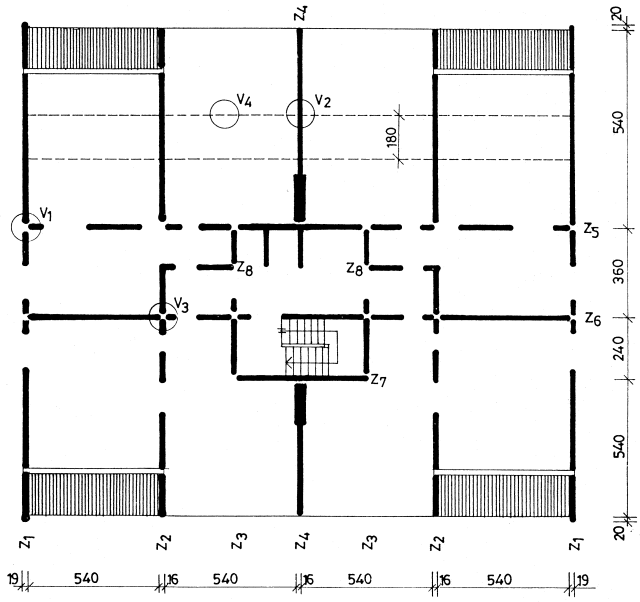

Fig. 11 - Layout of the three-story panel structure

The input for nonlinear behavior of the joints is defined as shown in the previous sections. The nonlinear analysis is executed with synthetic input accelerogram, constructed from two earthquakes. First, the main shock, Umbro Marchigiano N-S, 26.09.1997 with a_{max}=461.3cm/s^2 and the aftershock (reffered to as Example 2), from the same location, Umbro Marchigiano N-S, 06.10.1997 so a_{max}=369.9cm/s^2 (reffered to as Example 1). Input accelerogram is shown in Fig. 12.

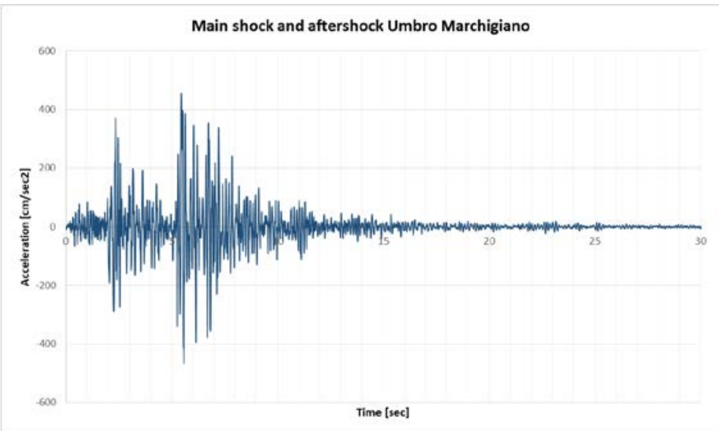

Fig. 12 – Synthetic input accelerogram Umbro Marchigiano

The obtained results are shown in the figures below. The results are presented by stories with the aim to be described the different behavior on the stories at any time during the analysis. From the figures, it is very easy to be described the development of the displacement, the degradation of the stiffness and also the behavior during the cyclic loading. In Figure 13 are shown the story displacements of the first storey during time, Figure 14 shows the stiffness degradation during the time of the first storey, while Figure 15 presents the first storey hysteresis diagrams – Force-displacement.

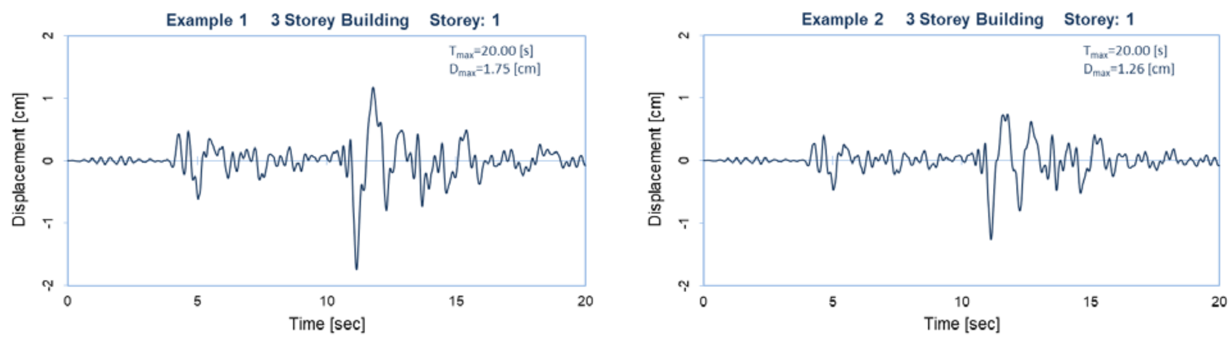

Fig. 13 - Structural response of the displacements (Time-Displacement diagrams, by stories)

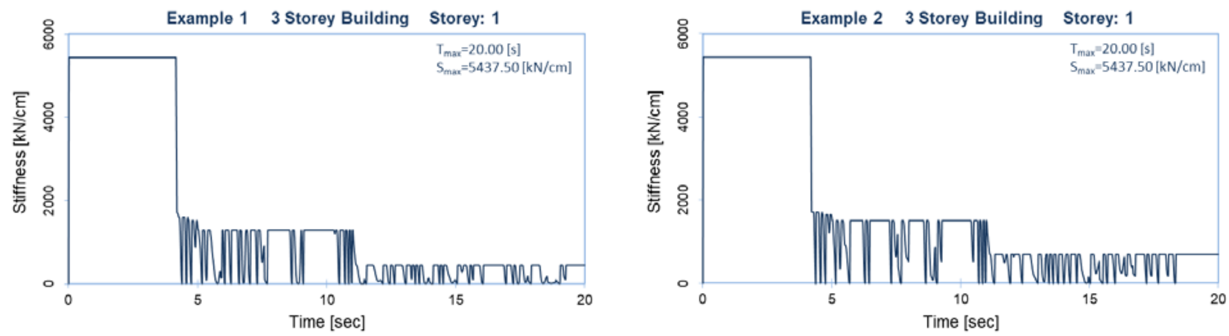

Fig. 14 - Structural response of the stiffness (Time-Stiffness diagrams, by stories)

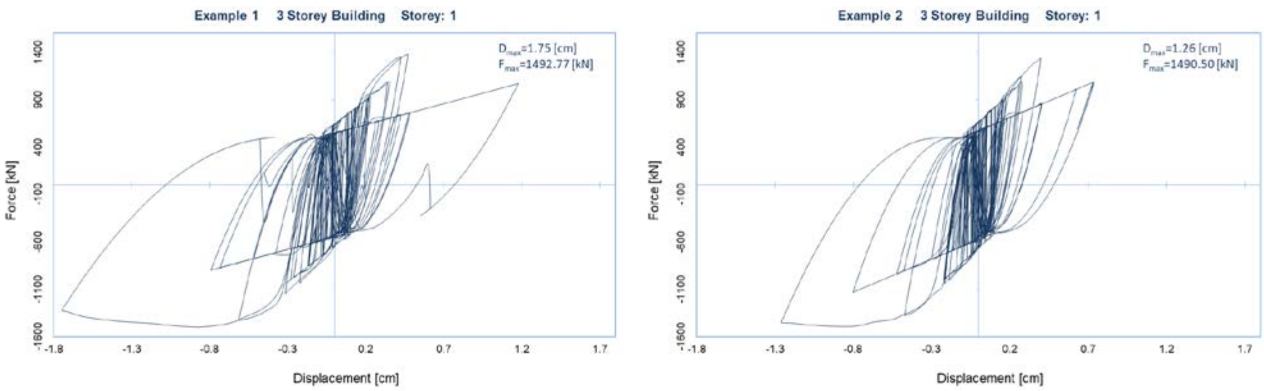

Fig. 15 - Structural response Force-Displacement (Force-Displacement diagrams, by stories)

4. CONCLUSION

Experimental investigations results are the most accurate basis for definition of strength, stiffness and deformability parameters of the structural elements and the whole structure. The models that have a twice smaller amount of uniformly distributed vertical and horizontal reinforcement represents ductile behavior of wall panels. The panels are characterized by moderate strength and stiffness, as well as, high deformability capacity. Diagonal cracks and considerable sliding along the contact surface of the panels and horizontal joints do not occur.

The proposed procedure enables design and analysis of economic prefabricated large panel RC structures to be built in seismic prone regions, by controlling the ductile behavior of the constituent elements, as well as, the whole structure. The procedure requires minimum experimental investigations for verification of the strength and deformability characteristics of the structural elements but only for the development of a particular large panel system. For panels design, stability and ductile behavior control, analytical methods in correlation with experimental results are used.

The defined structural dynamic response indicates that when the building is exposed to a major earthquake, foreshock or aftershock, there is a significant capacity utilization of the structure after the first earthquake. Therefore, multiple earthquakes with a relatively lower magnitude at the same location can cause a significant continuous stiffness and strength degradation, i.e., damage to the structural elements and the whole structural system. Therefore, it is necessary for buildings of vital importance to control the structural dynamic response to multiple coupled earthquakes recorded at the same location.

6. References

[1] Z. Bozinovski, P. Gavrilovic and D. Dojcinovski, Definition of Seismic Forces for Prefabricated Large Panel R/C Systems, According to YU-81, Eurocode (1, 2 and 8) And The Existing IZIIS Practice, INDIS '97 and CIB W-63, Yugoslavia, Novi Sad, November 12-14, 1997

[2] Z. Lj. Bozinovski, Experimental investigations performed for fragments of large-panel reinforced concrete systems, 11-th World Conference on Earthquake Engineering, Acapulco, Mexico, 1996.

[3] Z. Bozinovski, Experimental investigations of large panel reinforced concrete systems as a basis for aseismic design of stable and economic structures, SECED Conference - European Seismic Design Practice, Chester, UK, 1995.

[4] Bozinovski, Z., 1994. Nonlinear Behaviour of Prefabricated Large-Panel Reinforced-Concrete Systems Exposed to Dynamic - Seismic Loads, (in Macedonian), Doctoral dissertation, IZIIS, Skopje, Republic of Macedonia.

[5] Bozinovski, Z. 1994. Procedure for design and analysis of stable and economic prefabricated large panel reinforced concrete systems in seismically active regions, Proceedings of 10th ECEE, Vienna, Austria.

[6] Bozinovski, LJ., Z. & Velkov, M. 1993. Analysis of nonlinear behavior of large panel reinforced concrete precast systems exposed to dynamic effects, Proceeding of the second European conference on structural dynamics: EURODYN '93, Trondheim, Norway.

[7] Bozinovski, Z. & Velkov, M. 1990. Mathematical modelling of connections system of prefabricated large panel structures, Proceeding of 9 ECEE, Vol. 8, Moscow.

[8] Bozinovski, Z. & Velkov, M. 1987. Mathematical modelling of connections system for precast large panel structural systems (in Serbo-Croatian), 'Gradjevinar' No.7.

[9] Bozinovski, Z. & Velkov, M. 1986. Bearing capacity and deformability of joints of prefabricated large panel systems, Proceeding of 8 ECEE, Lisbon.

[10] Bozinovski, Z. 1986. Behaviour of large panel precast reinforced concrete structures in Japan, IISEE, Tsukuba, Japan.

[11] Bozinovski, Z. 1983. Nonlinear behavior of connections in prefabricated large panel systems for cyclic loads. Experimental and analytical Investigations, Master's thesis, (in Macedonian), IZIIS, Skopje, Republic of Macedonia.

[12] Delova, E. (2019). Design and analysis of stable and economic reinforced concrete structures with controlled and dictated ductile behaviour, Master thesis, August 2019, Skopje, R. N. Macedonia

[13] Poposka, M. (2019). Record selection based on structural dynamic response, Master thesis, November 2019, Skopje, R.N. Macedonia