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NUMERICAL ANALYSIS OF COMPOSITE STEEL CONCRETE STRUCTURAL SHEAR WALLS WITH STEEL ENCASED PROFILES

BY

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Abstract. The use of common reinforced concrete shear walls in high rise buildings is sometimes limited because of the large amount of reinforcement localized at the end of the element. A good alternative in avoiding this disadvantage is to use composite steel concrete structural shear walls with steel encased profiles. This solution used for high rise buildings, offers to designers lateral stiffness, shear capacity and high bending resisting moment of structural walls. The encasement of the steel shapes in concrete is applied also for the following purposes: flexural stiffening and strengthening of compression elements; fire protection; potentially easier repairs after moderate damage; economy with respect both to material and construction. Until now in the national and international literature poor information about nonlinear behaviour of composite steel concrete structural shear walls with steel encased profiles is available. A theoretical and experimental program related to the behaviour of steel concrete structural shear walls with steel encased profiles is developed at “Politehnica” University of Timişoara. The program refers to six different elements, which differ by the shape of the steel encased profile and also by the arrangement of steel shapes on the cross section of the element. In order to calibrate the elements for experimental study some numerical analysis were made. The paper presents the results of numerical analysis with details of stress distribution, crack distribution, structural stiffness at various loads, and load bearing capacity of the elements.

Key words: Composite construction; shear walls; numerical analysis.

1. Introduction

Composite construction utilizing steel and concrete are used in world wide almost as soon as the two materials became available for structural engineers. Since the beginnings composite construction is in continuous progress, every high rise building that rises up to the sky, being the result of a continuous research work in all developed countries. When speaking about composite construction it has to be mentioned that because of the development directions that governs the construction work, composite elements are used together with steel elements, reinforced concrete elements, for obtaining hybrid structures. Such composite elements that can be used together with perimeter frames in obtaining dual systems are the *composite walls*.

Composite walls are reinforced concrete walls with additional steel shapes or plates, being subjected to combined axial and lateral loads. Walls with additional shapes referred as composite steel–concrete shear walls, contain one or more encased steel shapes, usually located at the ends of the wall. The design principles of composite shear walls are included in specific codes-design of composite steel and concrete structures and in provisions regarding the design of buildings for earthquake resistance.

Although the research and specifications for composite construction, specially columns and beams, started very early, the design principles regarding composite structures, especially composite steel concrete shear walls, show a poor level of knowledge and in order to complete the design prescriptions, experimental studies in major laboratories and research centres, are in process.

2. Theoretical Aspects Regarding Composite Steel Concrete Shear Walls

The European standard EN 1994-1-1, Eurocode 4: *Design of Composite Steel and Concrete Structures: General Rules and Rules for Buildings*, describes the principles and requirements for resistance, serviceability and durability of composite steel concrete structures. The simplified design method for composite compression members, which is limited to doubly symmetrical and uniform cross section along the element length, gives the plastic resistance to compression of a composite cross section fully encased steel section as

$$N_{pl,Rd} = A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd}, \tag{1}$$

where: A_a , A_c , A_s represents, cross sectional areas of structural steel, concrete and reinforcement of the composite cross section, respectively; f_{yd} – design value of yield strength of structural steel; f_{cd} – design value of compression strength of concrete; f_{sd} – design value of yield strength of reinforcement

The plastic moment resistance of a doubly symmetric composite cross-section may be evaluated as follows:

$$M_{pl,Rd} = f_{yd}(W_{pa} - W_{pan}) + 0.5 f_{cd}(W_{pc} - W_{pcn}) + f_{sd}(W_{ps} - W_{psn}), \tag{2}$$

where: W_{pa}, W_{pc}, W_{ps} represents plastic section modulus for steel section, concrete and reinforcement of composite cross section, respectively (for the calculation of W_{pc} the concrete is assumed to be uncracked); W_{pan}, W_{pcn}, W_{psn} – plastic section modulus of the corresponding components within the region of $2h_n$ from the middle line of composite cross section for steel section, concrete and reinforcement of composite cross section, respectively; h_n – depth of the neutral axis from the middle line of cross section.

The resistance of a cross section to combined compression and bending may be calculated taking into account the design shear force, $V_{a,Ed}$, as follows: if the value of $V_{a,Ed}$ exceeds 50% of the design shear resistance, $V_{pl,a,Rd}$, is given by

$$V_{a,Ed} = \frac{1}{\sqrt{3}} A_v f_{yd} \gamma_{M0}; \tag{3}$$

the influence of shear force is taken into account by a reduced steel strength with the factor $1 - \rho$, where

$$\rho = \left(\frac{2V_{a,Ed}}{V_{pl,a,Rd}} - 1 \right)^2 , \tag{4}$$

with γ_{M0} – a partial factor for structural steel applied to resistance of cross section

3. Non-Linear Analysis

The non-linear behaviour of a structural element can occur from different causes as geometric non-linearities, material non-linearities. The geometric non-linearities are caused due to large deformations experienced by structures, which can cause geometric configuration changing. Non-linear stress–strain relationships are a common cause of non-linear structural behaviour. Many factors can influence material's stress–strain properties, including load history (as in elasto-plastic response), environmental conditions (such as temperature), and the amount of time that a load is applied (as in creep response).

The non-linear behaviour in composite steel concrete shear walls is due to the nonlinear properties of concrete and steel material, shear stud material, and also due to the interaction between these materials.

3.1 Reinforced Concrete Model for Plane Stress State

A phenomenological approach to concrete failure may be based on various classical criteria for yielding and failure of an isotropic material. Of course these criteria are suitably modified as to account for the different values of the compressive and tensile strength of concrete. Although all yielding and failure assumptions (apart von Misses) incorporate the different compression and tensile behaviours. Therefore, a combined criterion such as Cervenka together with von Misses criterion for compression was used. The finite element modelling of cracked concrete was achieved with distributed cracks. The reinforcement is supposed uniformly distributed. At material level, the stiffness matrix may be obtained by superposing the concrete and the reinforcement matrices.

3.2 Non-linear Analysis Software

The software called BIOGRAF is aimed to analyse reinforced concrete and composite steel-concrete elements in plane stress state. The two dimensional non-linear analysis is performed using incremental-iterative procedure (Fig. 1).

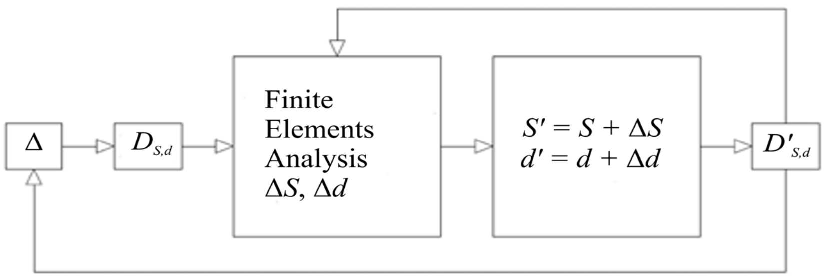

Fig. 1 – Incremental procedure diagram.

An incremental approach is adequate in like cases for describing the transition from one working stage to the next (load history analysis) within each loading step an iterative procedure is used. The software gives in all the elements, in all load steps, the displacements, stresses and strains in concrete and steel and the physical state of the finite element (cracked, uncracked, plastic state, crushed).

4. Composite Steel–Concrete Shear Wall Analysis

4.1 Models Presentation

Six proposed 1/3 scale elements CSRCW-1,…,6 were designed using the principles from the existing codes that make references to composite steel concrete elements. The aim of this paper is to predict non-linear behaviour, stress distribution along the cross section of the elements, crack distribution, structural stiffness at various loads, load bearing capacity of different types of composite steel–concrete shear walls, and comparisons with experimental results revealed by experimental tests which will be made during a research programme that started at our university. The differences between the six proposed element types are due to the arrangement of the steel shapes on the cross section of the wall and also due to the shape of the steel encased element. All six elements have a 3,000 mm height, 1,000 mm length and 100 mm depth. The encased steel profiles are $70 \times 70 \times 5$ mm squared tubular sections, welded wide flange sections $70 \times 70 \times 5 \times 7$ mm, $100 \times 70 \times 5 \times 7$ mm. The steel profiles are connected with the concrete by Ø13 mm headed shear stud connectors with 60 mm length. The reinforcement is made by vertical bars having Ø10/100 mm and horizontal bars of Ø8/150 mm. The confinement zones are made by Ø8/150 mm stirrups which hold together the longitudinal reinforcements from the ends of the elements. Both vertical and horizontal reinforcements are placed on both sides of the concrete wall and connected together with ties having Ø8/400/450 mm. Element CSRCW-6 is a traditional reinforced concrete shear wall and it is designed to have the amount of reinforcement concentrated at the end approximate to steel amount from other elements. The concrete used is C20/25 class, the reinforcements are made by steel S355 and the structural steel is Fe510. The details of all six types of steel concrete composite shear walls are presented in Figs. 2*a* and 2*b*. The elements are considered cantilevers subjected to horizontal loads applied as incremental loads, in the nodes from the top of the mesh.

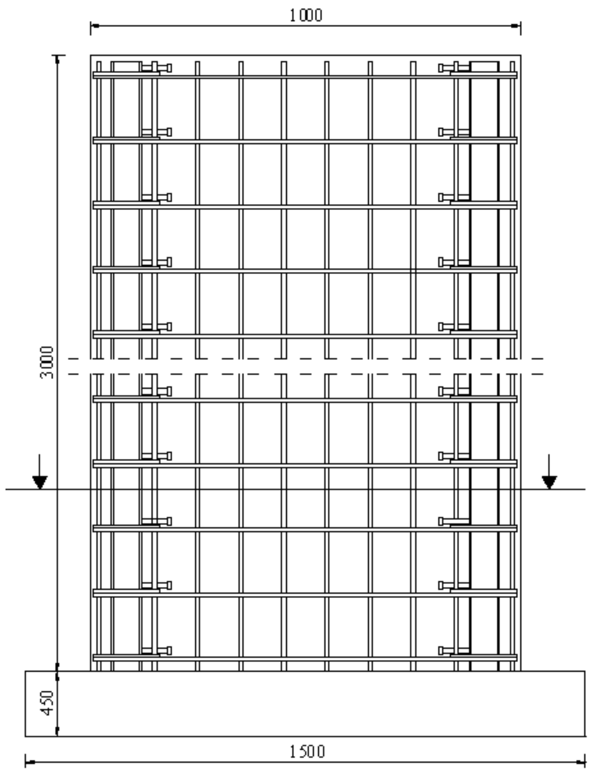

Fig. 2 *a* – Details of the steel concrete composite shear walls.

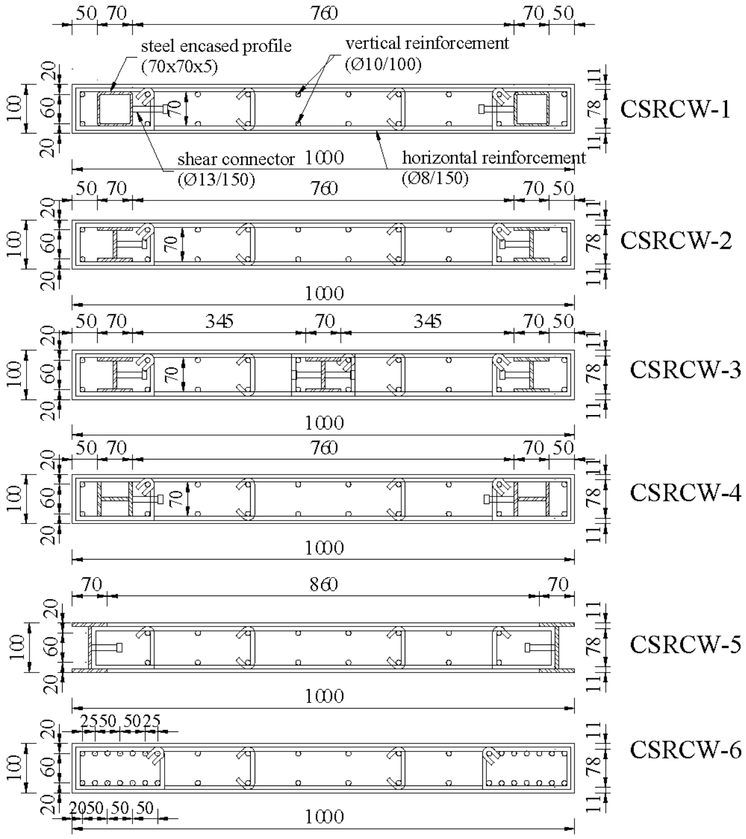

Fig. 2 *b* – Details of the steel concrete composite shear walls.

4.2. Analysis Results

All elements were analysed using approximatively the same loading increments, for avoiding the differences that could appear due to the influence of this parameter on the obtained results for all elements. The other parameters which gave the nonlinear behaviour are due to the cracks that appear in the tensioned concrete and the plasticization in compressed concrete, also because of the steel yielding. BIOGRAF software gives in all elements, in all load steps, the values of displacements, stresses and strains in concrete and steel and the physical state of the finite element (cracked, uncracked, plastic state, crushed). Evaluating the physical state of the finite elements, for all six element types, the following conclusions are obtained:

For element CSRCW-1, the elastic limit of the concrete is at a force value equal to F = 8.7 kN, and a corresponding displacement of 0.23 mm. From load step number 18 it can be noticed that the concrete is cracked near the steel encased element; this can produce during the experimental test concrete splitting which can cause the buckling of the steel element at a value of the force lower that the one obtained in the numerical analysis. Therefore, a bigger attention has to be given to the confinement zone and to the shear connectors, to avoid buckling failure until bending or share failure occur in the wall. The elastic limit of the element is at a force value equal to F = 149.2 kN.

The displacement at the elastic limit of the element is 9.66 mm. The wall collapse occurs at step 70 at a force value equal to F = 189.5 kN, resulting a capable moment equal to $M_{pl,Rd}$ = 568 kN.m, value that is bigger than one obtained with the simplified method from EC 4. The displacement until the moment of collapse is 21.1 mm. The collapse is specific to reinforced concrete failure, the concrete crashes when the reinforcement, including steel profile is in yielding. An important observation is that yielding occurs first in the steel encased element and after that in the reinforcement. For elements CSRCW-2,…,6 the elastic limits of the elements are different and also the values of crack moments and the ultimate forces and displacements. These values are indicated in the comparative Table 1.

Table 1

Comparison of Results on all Element Types

	CSRCW-1	CSRCW-2	CSRCW-3	CSRCW-4	CSRCW-5	CSRCW-6
Elastic limit force kN	149.1	154.6	162.4	144.2	119.6	110.5
Elastic limit displacement mm	9.66	9.96	9.19	9.23	9.47	8.90
Ultimate shear force kN	189.5	196.6	239.0	195.4	158.5	143.7
Ultimate displacement mm	21.10	20.10	18.40	19.50	20.55	20.52
Bending moment resistance kNm	568	590	717	586	475	431

As it can be observed from Table 1 the maximum shear force is obtained at element CSRCW-3 which has an encased profile at the middle of the cross section. So it can be noticed that the amount of steel in composite wall cross sections influences the value of ultimate shear force. Also for element CSRCW-6, which is the ordinary reinforced concrete, is observed that it has the lowest shear capacity although the amount of vertical reinforcement is equal to the amount of steel from the encased element.

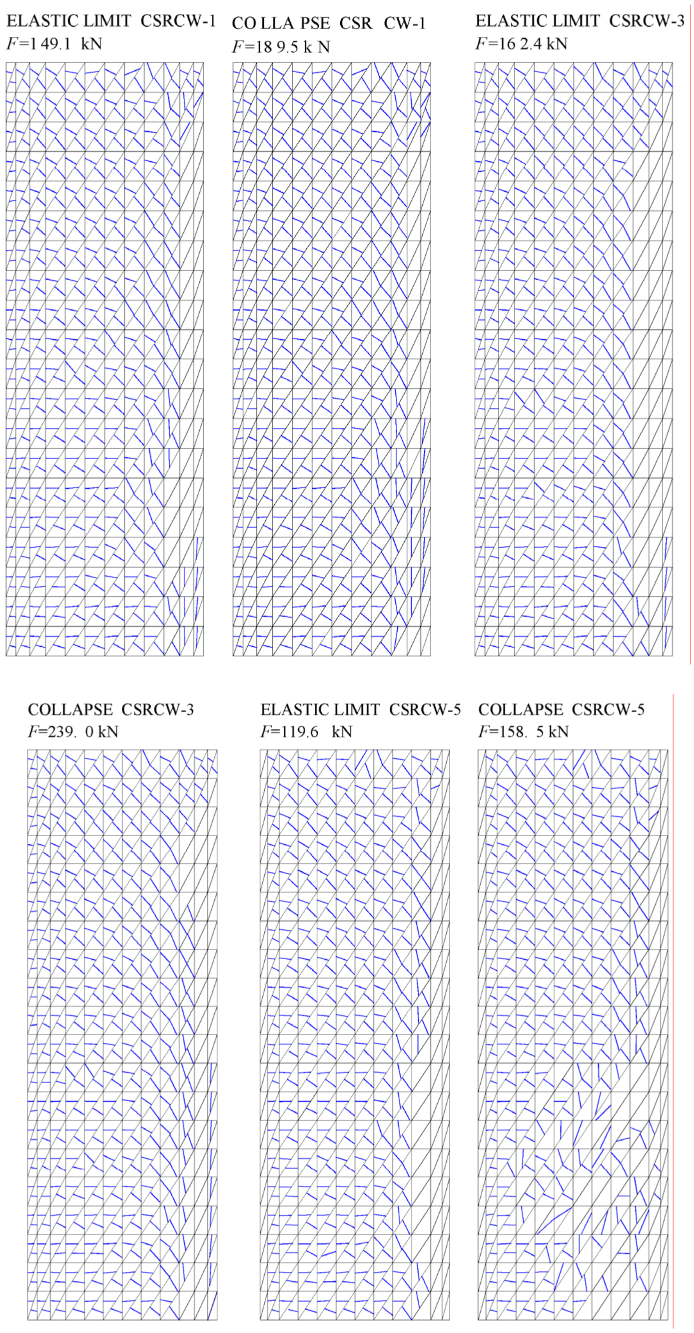

Fig. 3 – Crack distribution at different staps.

Fig. 3 presents the crack distribution in the elements at various load steps. First crack appears in all elements after the elastic limit of the concrete is reached. The evolution of the cracks is a normal one, cracks being distributed uniformly on the elements surface in all six elements. The vertical cracks in the compression zone, which appear in all six elements, but at different load stages, also show the splitting tendency of concrete from the structural steel. The cracks from the upper part of the elements are due to the fact that loads are applied in every point from the top of the mesh. The difference between crack orientations is visible at a larger scale that one presented in this figure. Because of the lack of space, crack distribution is presented only on elements CSRCW-1, CSRCW-3, CSRCW-5.

Fig. 4 presents a comparison between force *vs.* displacement curves obtained for all six element types. All six elements experience stiffness decreasing after concrete cracking, but this decrease is not as evident as that produced by steel yielding and concrete plasticization. The stiffest element is CSRCW-3 with three encased steel elements and the less stiff is CSRCW-6, the reinforced concrete wall, the other walls stiffness varies between these limits.

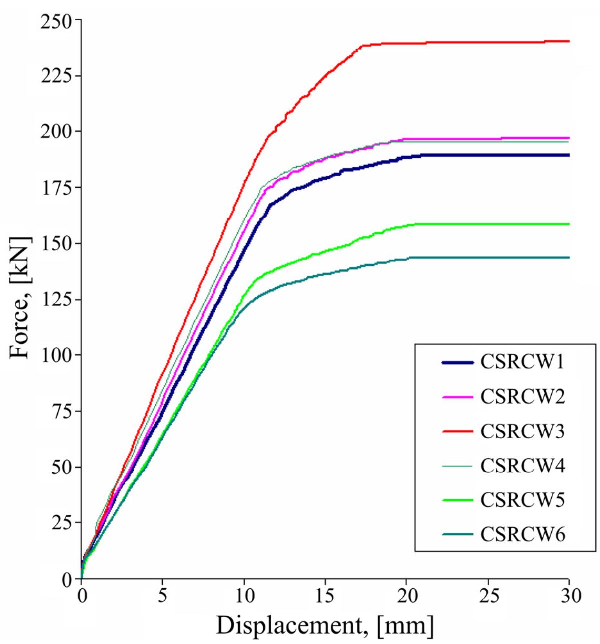

Fig. 4 – Comparative force *vs.* displacement curves.

Although the maximum shear force resistance is obtained for CSRCW-3, because of the higher stiffness the ultimate displacement is smaller than for the other elements with a smaller shear resistance but with a higher value of ultimate displacement. This observation is better presented in Fig. 5. The displacement ductility is known as the ratio value between the ultimate displacement and the displacement when the first steel element yields. The displacement ductility is a parameter that defines better the capacity of a structure in dissipating energy during seismic events. The maximum ductility is experienced by reinforced concrete element. Although it is possible that during the experimental tests that will be carry on, on same experimental elements with those analysed in this paper , to obtain values of ductility little different from those obtained in numerical analysis. This could happen because the programme doesn't take into account the friction between crack faces.

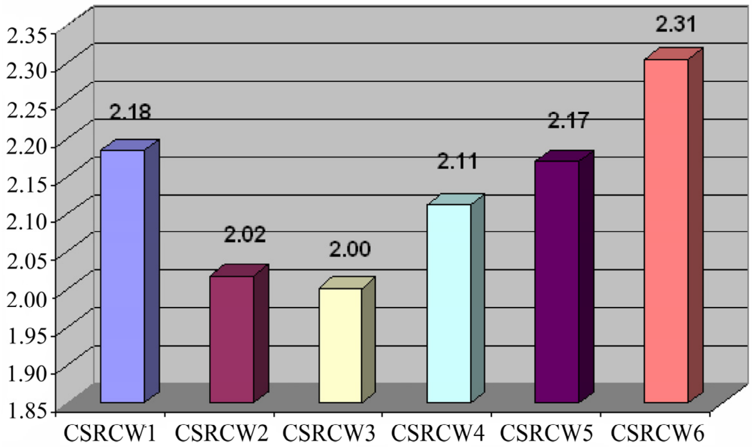

Fig. 5 – Comparative displacement ductility.

5. Conclusions

The national and international literature studied show a poor level of knowledge in the field of using of composite shear walls at the multi-storey building. The observations on composite steel concrete structures subjected to important earthquakes made possible the improving of performances of structural systems that use steel concrete composite shear walls. Using the information presented above and the information from specific literature the following conclusions can be formulated:

1. Non-linear analysis were made on six different types of composite steel reinforced concrete shear walls with steel encased profiles.

2. The composite steel concrete shear walls have an important plastic resistance to compression, combined compression and bending and shear resistance. Also the stiffness value increases as the amount of steel increases on the cross section of the element too.

3. The displacement ductility has values that not differ very much for all elements, because the amount of the steel is almost the same.

Experimental tests will be made in order to confirm the numerical analysis results.

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ANALIZE NUMERICE A PEREŢILOR COMPOZIŢI OŢEL–BETON CU ELEMENTE METALICE ÎNGLOBATE

(Rezumat)

Utilizarea sistemului tradiţional de pereţi din beton armat la realizarea structurilor înalte poate fi câteodată limitată datorită cantităţii mari de armătură concentrată la capătul elementului. O alternativă în evitarea acestei probleme o constituie utilizarea pereţilor compoziţi oţel–beton cu profile metalice înglobate. Această soluţie, utilizată în cazul clădirilor înalte, oferă proiectanţilor rigiditate laterală , capacitate de forfecare şi momente capabile mari ale secţiunilor. Înglobarea profilelor metalice în beton se realizează şi datorită faptului că ele conferă rigiditatea şi rezistenţa elementului compozit oţel–beton. Totodată soluţia oferă o protecţie la foc corespunzătoare în ceea ce priveşte profilele metalice care sunt protejate faţă de

acțiunea focului. Până în prezent literatura națională și internațională oferă foarte puține informații legate de comportarea pereților cu profile metalice înglobate. În cadrul Universității „Politehnica" din Timişoara se desfăşoară un program de studii teoretice şi experimentale cu scopul de a obține mai multe informații în ceea ce priveşte comportarea pereților din beton armat cu profile metalice înglobate. În cadrul programului de cercetare se au în vedere şase tipuri de pereți, la care diferențele se referă la modul de aranjare al profilelor metalice şi la tipul profilelor metalice utilizate. În faza actuală au fost efectuate analize numerice neliniare cu scopul de a obține informațiile necesare pentru viitoarele încercări experimentale.

Se prezintă rezultatele analizelor numerice efectuate pe cele şase tipuri de elemente cu prezentarea distribuției eforturilor unitare, distribuția fisurilor, rigiditatea elementelor la diferite niveluri de solicitare şi evaluarea capacității portante a elementelor.