SEISMIC PERFORMANCE OF PRESTRESSED PRECAST HOLLOW CORE SLABS-RC BEAM CONNECTIONS

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Abstract

The main goal of the research presented in this paper was to investigate experimentally seismic performance of the integral assemblage consists of prestressed precast hollow core slabs (HCS), RC beams and cast in situ topping for monolithization. The request was industry-driven in order to speed-up the time of construction of Mixed-Use Center in Skopje, North Macedonia with area of over 300.000m^2 through replacement of certain cast in situ RC slabs with precast HSC. The HCS are designed for bearing vertical loads only and produced at PUT Inzenering factory (http://putinzenjering.com/about-us/?lang=en) under controlled site conditions. Design of the models was performed at IZIIS in Skopje and testing was performed in situ at Put Inzenering facility in Nish, Serbia, in June-July 2019.

The models were designed and constructed in real scale. The original models were designed and built according existing regional construction practice whereas the improved models were designed and built with insertion of additional reinforcement Φ12 B500 B in the second and fifth opening of the HCS. A tailor made experimental program to assess the seismic performance of the models was carried out. Two different prototype configurations with all together nine models were tested under quasistatic cyclic loading:

- Models under gravity loads and seismic forces in vertical direction – VS models (2 original + 4 improved - 6 models in total)
- Models under gravity loads and seismic forces in horizontal direction – HS models (1 original +2 improved - 3 models in total)

The tests results shown that the original models, in both configurations, have poor seismic performance whereas the improved ones shown better seismic performance. Presented in the paper are selected parts from the activities related to design, construction, instrumentation and testing of the models.

Keywords: seismic performance; precast hollow core slabs; quasi-static testing, ultimate resistance.

1. Introduction

1.1 Seismic performance of precast hollow core slabs (precast HCS) – brief

The RC precast buildings are widely used in European construction practice with more than 50 million square meters of buildings per year. Such buildings house a predominant share of industrial facilities in many European countries. Recently they are also used for multi-story office buildings and shopping centers housing thousands of people.

Recent earthquakes clearly demonstrated that the potential seismic risk of these systems is high [1]. The field experience shown that the main causes of the damage to the investigated precast system are due to: failure of the connections, as the main cause of damage and collapse; than lack of mechanical connections between the columns and roof girders in old buildings and in supposedly aseismic regions; lack of ties; insufficient in-plain stiffness of the roof/floor structures; torsional response due to asymmetric stiffness distribution; poor detailing of hoop reinforcement in columns; unpredicted large displacements associated with too-short seating and poor connections ;poor foundation in soft soil; detachment of claddings, etc., [2].

To fill the gap on the knowledge of seismic performance of precast structures with specific reference to connections and their deformability, two EU research projects SAFECAST – Performance of innovative mechanical connections in precast building structures under seismic conditions (2009–2012) [3,4] and SAFECLADDING - Improve Fastening Systems of Cladding Panels for Precast Buildings in Seismic Zones (2012-2015) [5] have been carried out, recently.

However, observations from the past earthquakes point out also one specific issue related to the seismic performance of the connection between the hollow core slabs and perimeter beam. It was observed that if the connection fail than section of the floor could collapse leading to a partial, or eventually full collapse of the building, [6]. Such example was seen in Northridge (01.17.1994) earthquake where collapse of a portion of car-parking building was appeared due to the hollow-core precast slab losing its sets and collapsing (Fig.1).

Fig. 1 Collapse of a complete section of floor, [6]

1.2 Goal and models for testing

The above presented specific issue is addressed below. The main goal of the research is to investigate experimentally seismic performance of the integral assemblage consists of prestressed precast hollow core slabs (HCS), RC beams and cast in situ topping for monolithization (slabs-beams connections). The request came from the construction company LIMAK doo Skopje who wants to replace RC slabs at certain position of the SKOPJE MIXED-USE Center [7] with prestressed precast HCS-s in order to speed the construction process. Design of the models was performed at IZIIS in Skopje, while construction and the testing were performed in situ at Put Inzenering Facility in Nish, Serbia, [8] in June-July 2019. In order to provide reliable results, the models were chosen to be designed and constructed in real scale.

It is important to be noted that in each group of 3 models there is 1 original model which was designed according to the existing engineering practice of the manufacturer and does not have reinforcement inside of the openings of the HCS (Figs. 6 and 10) and 2 improved models with additional reinforcement Φ12 B500 B in the second and fifth opening of the HCS (Figs.7 and 11).

Two different prototype configurations with all together nine models were tested, (Table 1).

Table 1. Summary of tested models

Configuration	Span [m]	Model description
VS configuration	l= 6.0m	VS – Model 1 (original connection)
		VS – Model 2 (improved connection)
		VS – Model 3 (improved connection)
	l= 8.0m	VS – Model 1 (original connection)
		VS – Model 2 (improved connection)
		VS – Model 3 (improved connection)
HS configuration	l= 2.4m	HS – Model 1 (original connection)
		HS – Model 2 (improved connection)
		HS – Model 3 (improved connection)

Presented further in the text are selected parts from the activities related to design, construction, instrumentation and testing of the models. Detailed information could be found in [9].

2. Experimental Quasi-Static Test on Full Scale Models

2.1 Precast prestressed hollow core slabs

The precast prestressed hollow core slabs (HCS) which are subject of the tests are produced at PUT Inzenering factory (http://putinzenjering.com/about-us/?lang=en) under controlled site conditions. The production of hollow core slabs takes place on runways by the method of extrusion of special concrete with the help of slipform pavers which form slab section with continual interior hollow cores. The production width of slabs is 120cm, the length is variable whereby thickness depends on load and the span of slabs (Fig. 2). The thickness of slabs can be 20cm, 25cm, 30cm, 35cm and 40cm. Depending on load, required span and water resistance, the values are read from the catalog and the types of slabs selected.

Fig. 2 Manufacturing and mounting of the precast prestressed hollow core slabs (http://putinzenjering.com/about-us/?lang=en)

The following specific precast prestressed hollow core slabs were produced and tested (Fig. 3):

- PUT INZENJERING - ECHO SC 20x120, with span l = 6.0m
- PUT INZENJERING - ECHO SC 20x120, with span l=8.0m

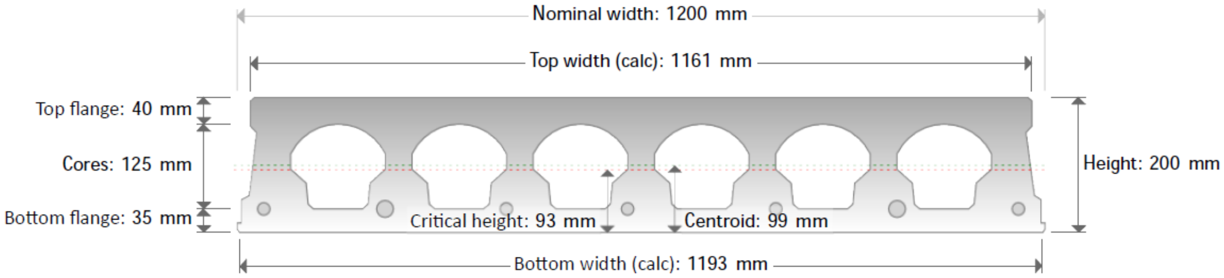

Fig. 3 Cross-section of the precast prestressed hollow core slabs

The HCS are designed for vertical loads according to the EN 1992-1-1:2004, [10]. These elements are constructed with the same section, same number of cables and same prestressed force, for both spans of 6m and 8m and for both configurations (5 cables with diameter 9.3mm, and 2 cables with diameter 12.5mm prestressed at 1116MPa). and with the concrete grade of C50/60. The concrete grade of the element was C50/60 and of the topping C30/37. The total depth of the topping for monolitization is 7 cm.

2.2 Equipment for quasistatic testing

For the needs of these experiments Quasi Static Hydraulic Jack with maximum force capacity of 200 tons in push-pull direction and maximum stroke of +/- 250 mm with existing steel supporting structure was used (Fig. 4). This jack is originally designed for applying cyclic force in horizontal direction.

However, for the needs of imposing vertical seismic loads on the VS model configuration additional steel supporting frame was designed at IZIIS and constructed by the Feromont Engineering company from Skopje (http://feromont.mk/) (Fig. 5).

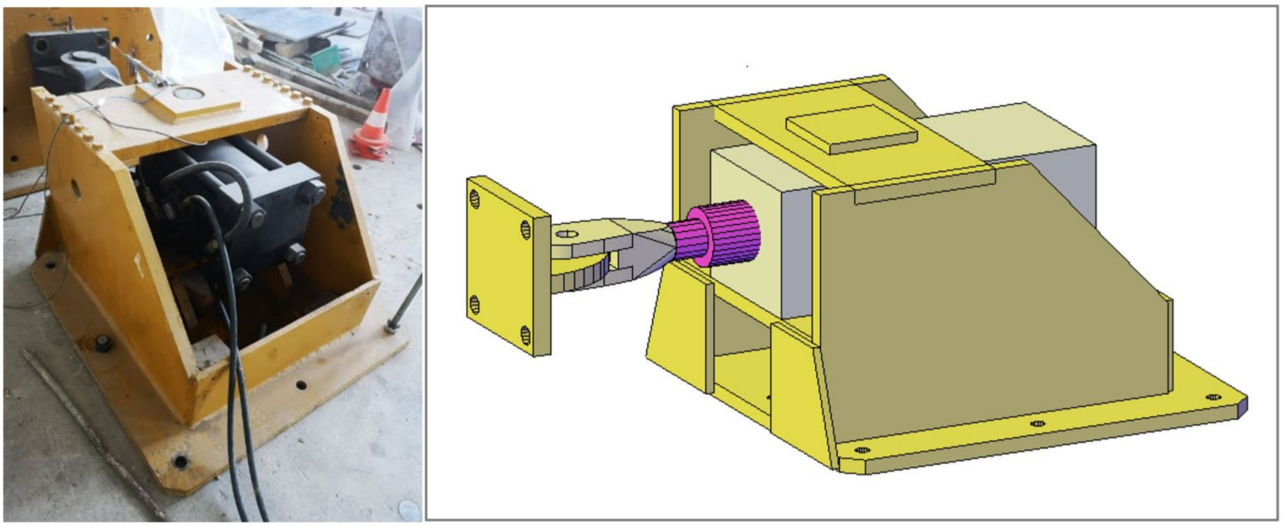

Fig. 4 IZIIS' Quasi Static Hydraulic Jack (IZIIS Laboratory)

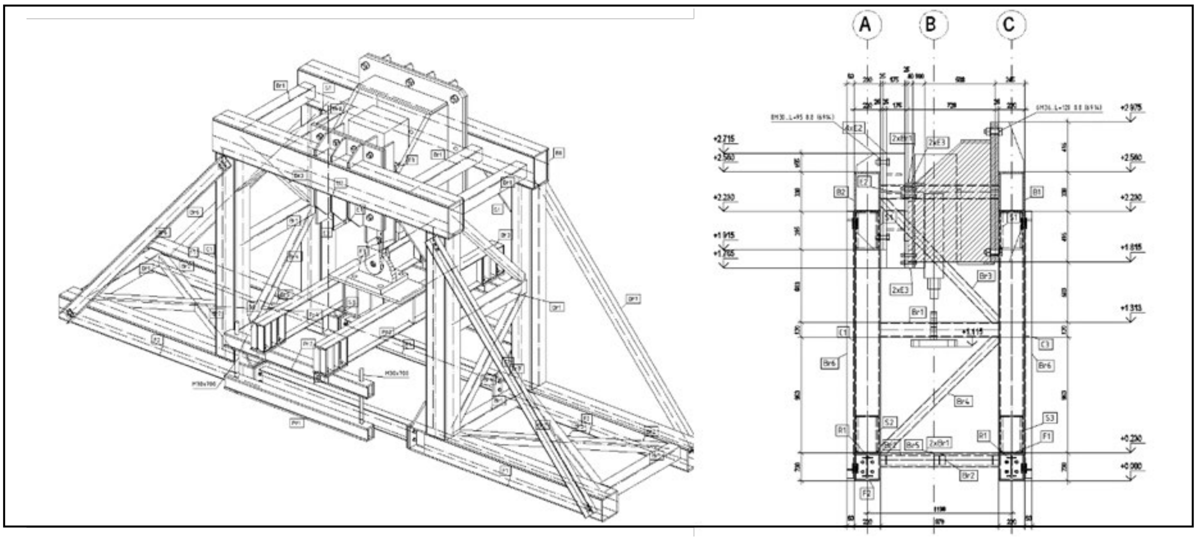

Fig. 5 Supporting steel structure for VS model configuration

2.3 Design and construction of models for quasi-static testing

2.3.1 Design and construction of models under vertical seismic loads (VS models)

Design of models under vertical seismic loads (VS models)

Models subject to vertical seismic loads (VS_6m -3 models and VS_8m -3 models) are consisted of two RC monolithic beams, prestressed precast hollow core slabs (HCS) and cast in situ topping for monolithization (Fig. 6 – original models and Fig. 7 – improved models).

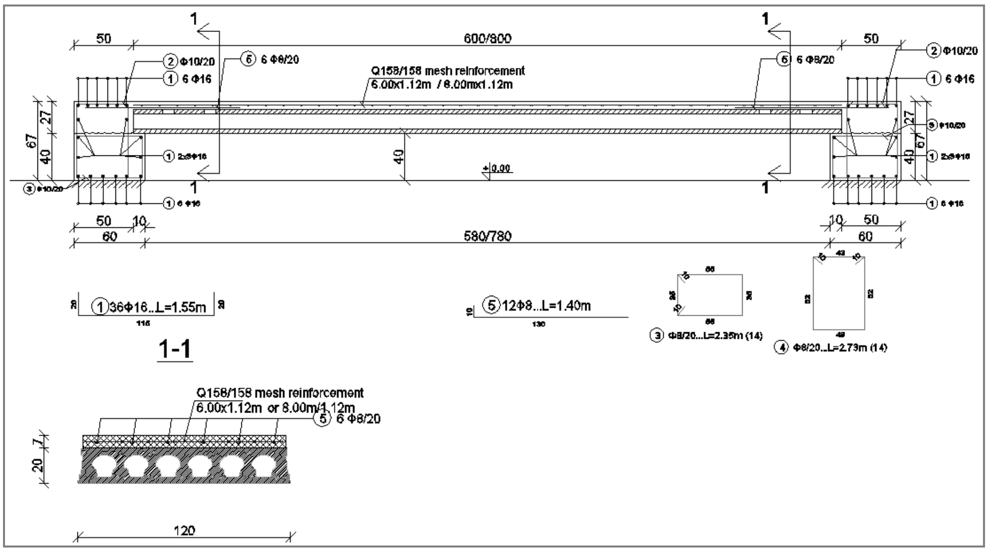

Fig. 6 Reinforcement in the original VS models

The supporting beams are fixed to the ground with RC ground slab and reinforcement that goes from the bottom of the beam into the slab. The supporting beams are concreted in 2 phases. Their dimensions are 60cm x 77cm (10+40+27), which represent the real situation in the building where these elements will be constructed. The supporting beams are reinforced with 6BΦ16 in the top and bottom of the beam, 4 rows with 2BΦ16 as along the height of the beam and as transversal reinforcement, stirrups BΦ10/20cm are used, (Figs. 6 and 7).

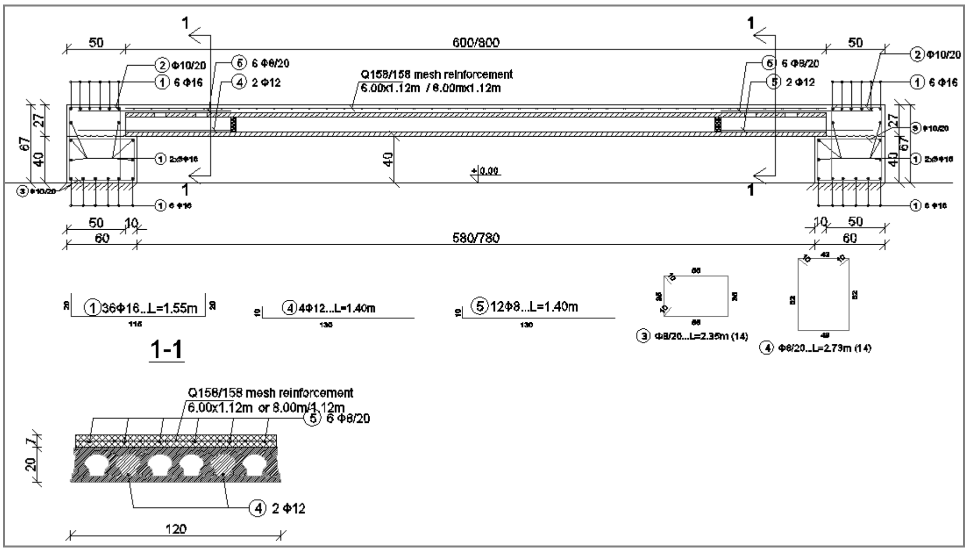

Fig. 7 Reinforcement in the improved VS models

The prestressed HCS and supporting beams are monolithized with cast-in situ topping with depth of 7cm and reinforcement of Q158 mesh, (Figs. 6 and 7). For continuation of reinforcement in the topping, reinforcement BΦ8/20cm is placed inside of the reinforcement cage in the upper part of the beam, and these rebars are continued in the topping of the slab (above the HCS). The models are arranged in one line divided with 5cm XPS, (Fig. 8).

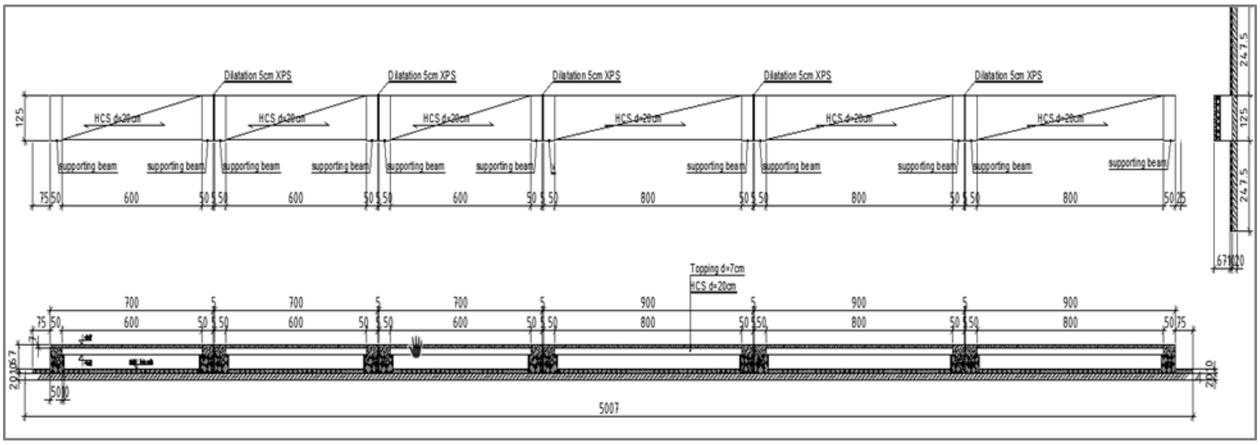

Fig. 8 Disposition (floor plan and vertical section) of the VS models

Construction of models under vertical seismic loads (VS models)

The models were constructed at the Put Inzenering Facility in Nish, Serbia according to the design documentation. The construction was performed by Put Inzenering. Concrete classes C50/60 has been used for the prestressed precast HSC and reinforcement class B500B.

The construction was carried out in two phases. The first phase is concreting of RC ground slab and the first 50cm of the height of the beam. Then, prestressed HCS with length of 6m and 8m were positioned on the beams, with 10cm a seating length. The next step was putting reinforcement mesh at 3.5cm above the HCS (in the middle part of the topping). For continuity between the mesh in the topping and the supporting beam reinforcement, BΦ8/20cm is placed inside of the reinforcement cage in the upper part of the beam, and these rebars are continued in the topping of the slab, (Fig. 9).

In the two improved models of each group, additional BΦ12 reinforcement is placed in the second and fifth opening. These openings were latter filled with concrete in the second phase of concreting.

Fig. 9 On site view of the VS models

After placing of these additional reinforcements next step was concreting of the second phase the elements. Meaning that the beam was filled with 27cm of concrete (reaching full height of 10+40+27cm) and topping above the Hollow Core Slab with 7cm depth.

2.3.2 Design and construction of models under horizontal seismic loads (HS models)

Design of models under horizontal seismic loads (HS models)

Each of the model subject to horizontal investigation (HS_2.4m) consists of one supporting RC monolithic beam that represent support of the prestressed HCS with width of 60cm + 120cm + 60cm (total width of 240cm) on one side while the other is left free standing on rollers (Fig. 10 – original model, Fig. 11 – improved models and Fig. 12). These HCS elements are constructed with the same section and same number of cables as for VS models, (Figs. 3 and 12).

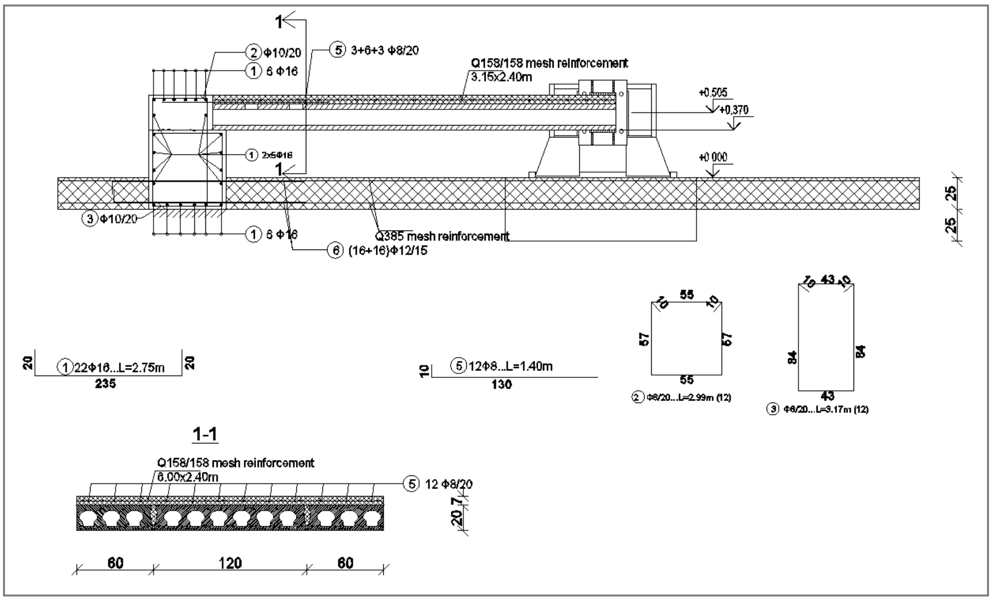

Fig. 10 Reinforcement in the original HS models

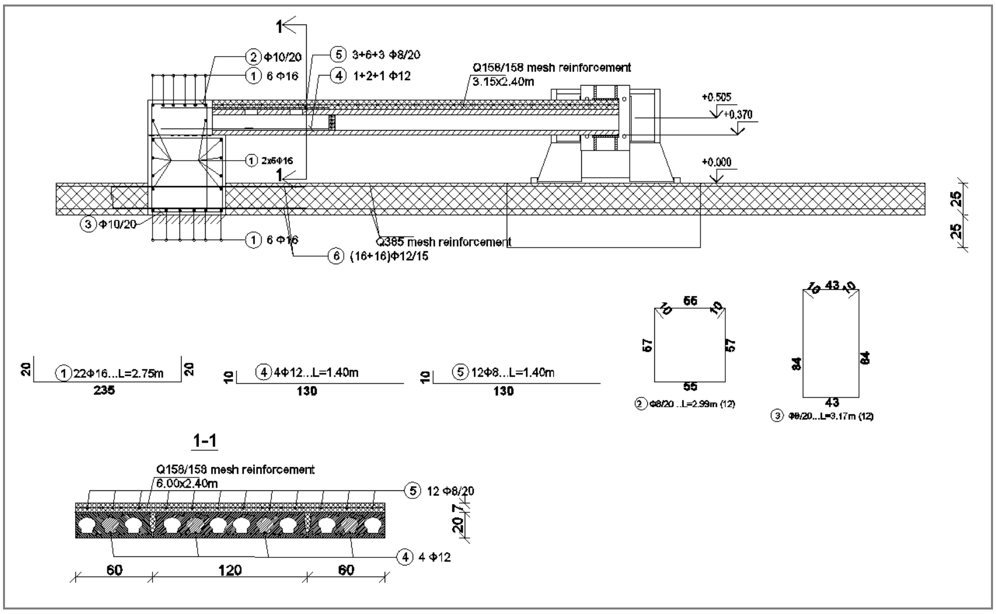

Fig. 11 Reinforcement in the improved HS models

The supporting beam is fixed to the ground with RC ground slab and reinforcement that goes from the bottom of the beam into the slab. The supporting beam is concreted in 2 phases. Its dimensions are 60cm x 89cm (25+37+27), which represent the real situation in the building where these elements will be constructed. The supporting beams are reinforced with 6BΦ16 in the top and bottom of the beam, 5 rows with 2BΦ16 along the height of the beam and as transversal reinforcement, stirrups BΦ10/20cm are used, (Figs. 10 and 11). The special foundation was design for supporting the hydraulic jack. The prestressed HCS and supporting beam are monolithized with cast-in situ topping with depth of 7cm and reinforcement of Q158 mesh, same as for VS models, (Figs.10 and 11). The horizontal force was imposed on the free-standing end of the model toward tailored made steel element (Fig. 12).

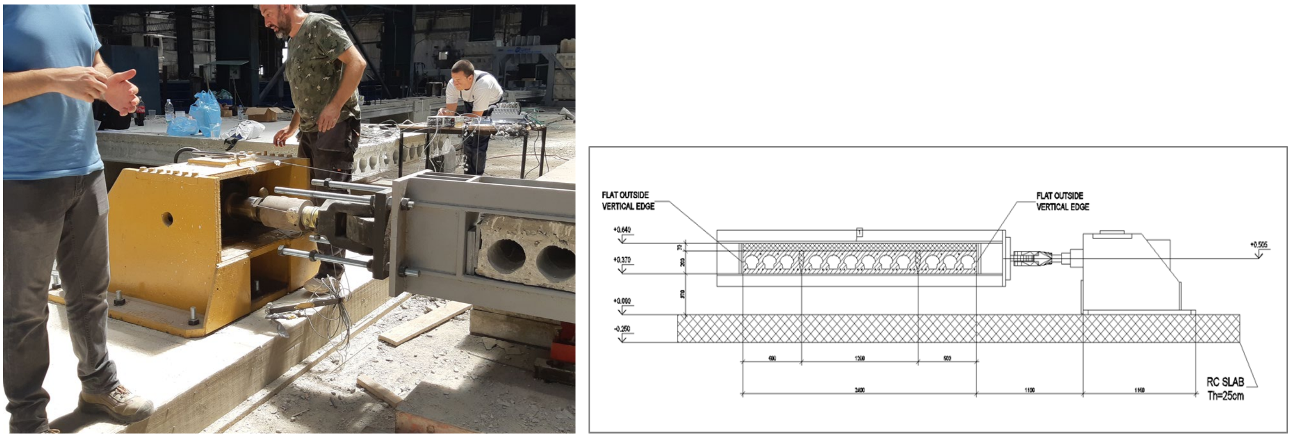

Fig.12 On site view and cross-section of the HS models

Construction of models under horizontal seismic loads (HS models)

In accordance with the designed proportions, the models were constructed at the Put Inzenering Facility in Nish, Serbia. The construction was performed by Put Inzenering. The build-in materials and phases of constructions are the same as for the VS configuration models.

During the concreting, 16 concrete specimens (8 per each configuration) were molded and they were tested at the age of 28 days at the Laboratory of construction materials, Faculty of Civil and Architectural

Engineering in Nish, Serbia [11]. The compressive strength of concrete was determined using SRPS ISO 4012:2000 standard and its value was 65.36MPa for HCS and between 52.86 and 62.39 MPa for the topping.

2.4 Instrumentation and testing of models for quasi-static testing

Half and full cycle loading program was imposed on the models. Force control was applied for all 9 tests. The number of the repeated cycles at the selected level of displacement was tuning during testing in accordance with the observed performance of each model.

2.4.1 Instrumentation and testing of models under vertical seismic loads (VS models)

Response of each model response was monitored by high speed data acquisition system consisting of 5 displacement transducers (LVDT) and 15 strain gages (SG), among which 5 on concrete and 10 on steel reinforcement, providing information about relative displacements, deformations and strain at selected points. The complete instrumentation set-up is given in Fig. 13.

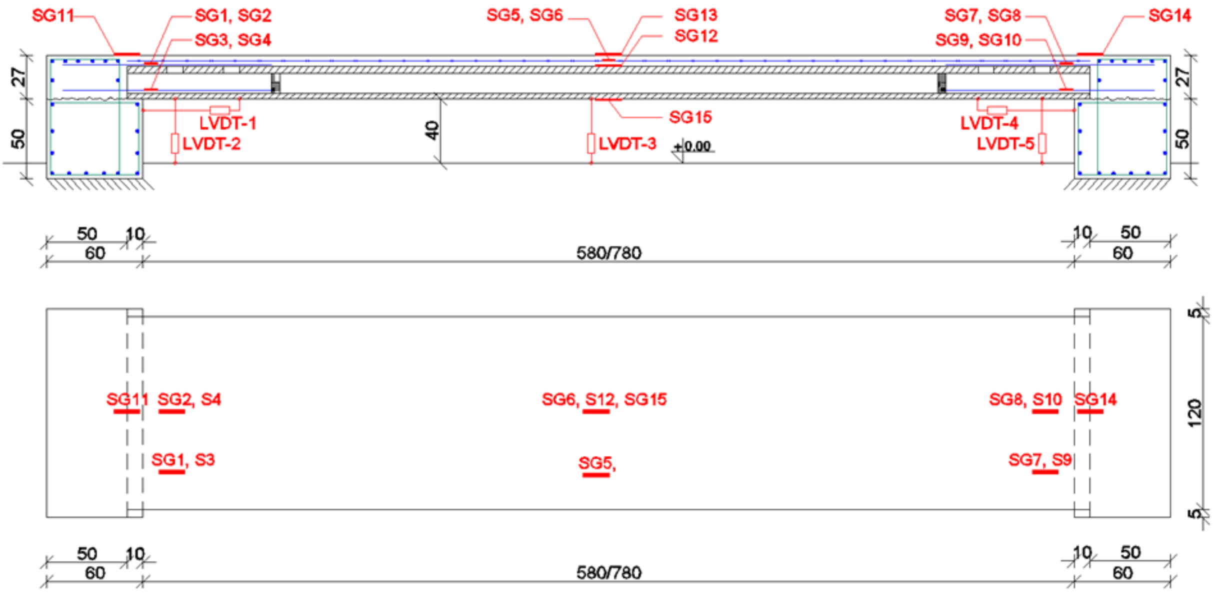

Fig. 13 Instrumentation of the VS models

During the testing of each of the 6 VS models' series of steps were performed (Fig. 14):

1. Mounting of the Quasi Static Hydraulic Jack and supporting structure on the exact position for testing (middle of the span of the model)
2. Placing additional concrete blocks as counter load of the Hydraulic Jack
3. Calibration of testing equipment and transducers installed on the models
4. Imposing of the loads according to the testing program
5. Visual observation of model performance and marking of the appeared cracks
6. De-mounting of the equipment and transfer to the subsequent position for testing

Observed damages appeared to the models during testing (selected photos) are presented in the Fig. 15.

Fig. 14 Mounting of the Hydraulic Jack with supporting structure and additional concrete blocks

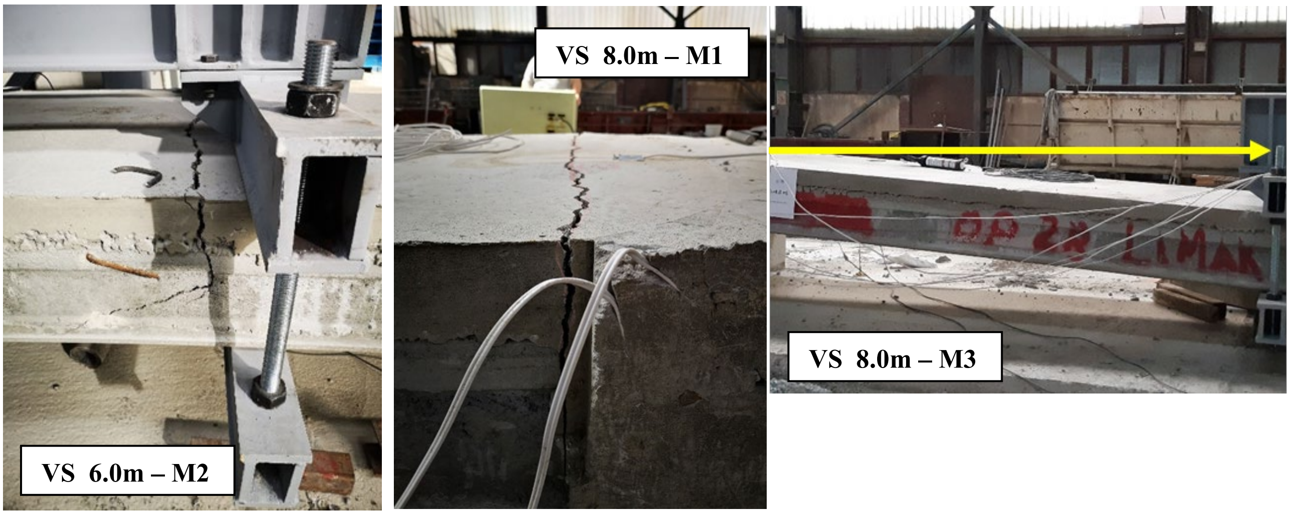

Fig. 15 Damage observed during testing of VS models

2.4.2 Instrumentation and testing of models under horizontal seismic loads (HS models)

Response of each model response was monitored by high speed data acquisition system consisting of 6 displacement transducers (LVDT) and 6 strain gages (SG), mounted on the reinforcement, providing information about relative displacements, deformations and strain at selected points. The complete instrumentation set-up of improved models is given in Fig. 16.

During the experimental investigation of each of the 3 HS models' series of steps were performed:

1. Mounting of the Quasi Static Hydraulic Jack. Only one anchor system was designed and constructed, so for each experiment the Hydraulic Jack was rotated around this anchor system, (Fig. 12)
2. Calibration of testing equipment and transducers installed on the models
3. Imposing of the loads according to the testing program
4. Visual observation of model performance, marking of the appeared cracks and monitoring of measured response
5. De-mounting, rotation and mounting of the hydraulic jack for the subsequent test

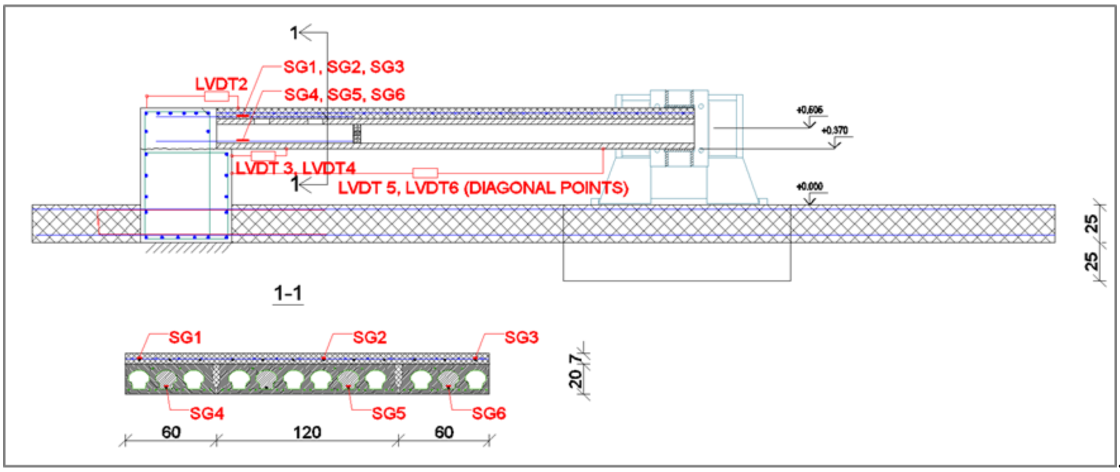

Fig. 16 Instrumentation of HS models

Selected photos during testing of HS models are given in the Figure 17.

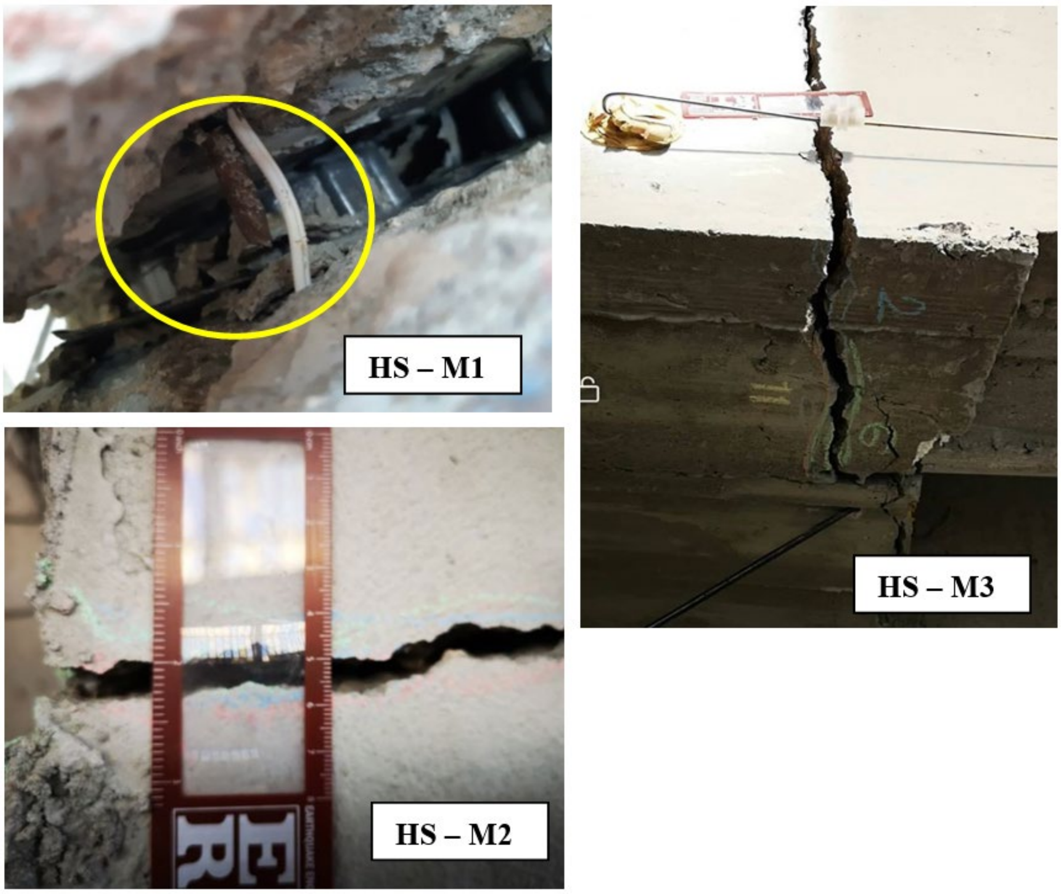

Fig. 17 Damage observed during testing of HS models

3. Observation from tests and discussions

The main goal of the research was to investigate experimentally seismic performance of the integral assemblage consists of prestressed precast hollow core slabs (HCS), RC beams and cast in situ topping for monolithization.

From observations during tests and first insight into the measurements the following can be concluded:

For VS configuration of the models

The original models shown unfavorable performance under vertical seismic forces. The failure mechanism appeared due to wide cracks in the top cross-section of the beam-slab connection, separation of the topping and presstressed HCS due to the loss of adhesion and cracks in the bottom cross-section of HCS (Fig. 15).

The improved models shown enhanced performance under vertical seismic forces. The failure mechanism is similar with the above described however the registered ultimate resistance was higher which pointed to the certain effectiveness of the proposed technical solution for improvement.

For HS configuration of the models

The failure mechanism is similar for all three models and appeared due to wide cracks in the top cross-section of the beam-slab connection, rupture in the top tension reinforcement, and separation of the topping and prestressed HCS due to the loss of adhesion (Fig. 17). Although there is slight increase in the ultimate resistance of the improvement HS models, generally, it can be concluded that the proposed technical solution for improvement is more efficient for vertical than for horizontal seismic forces.

From the observation of the performance of the models during testing and preliminary insight in the experimental results it could be concluded that the improved models in both configurations (VS and HS) shown better seismic performance than the original ones. Detailed interpretation of the measured results as well as recommendation for further research regarding numerical modeling can be find in [9]. Publishing in relevant journals in anticipated.

4. Acknowledgements

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