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Партизански одреди 24, П.Фах 560, 1001 Скопје Македонија

MASE
MACEDONIAN ASSOCIATION OF STRUCTURAL ENGINEERS
Partizanski odredi 24, P. Box 560, 1001 Skopje Macedonia

SS - 11

mase@gf.ukim.edu.mk
http://mase.gf.ukim.edu.mk

Denis POPOVSKI[1], Petar CVETANOVSKI[2], Mile PARTIKOV[3]

THE EFFECTS OF THE PRE-STRESSING BY CONTROLLED IMPOSED DEFORMATIONS OF CONTINUOUS COMPOSITE BEAMS

SUMMARY

The effects of pre-stressing a composite continuous beam at the middle support with imposed controlled deformations are incomparable. Testing of these effects is the main research point of interest of complex experimental and theoretical research of the behavior of continuous composite beams. In this report the methods of the testing are given for two same continuous composite beams, where one is pre-stressed. Also, the results of the testing and the theoretical research with analytical models are given, with comparison analysis of the behavior of the two beams.

Key words: composite structures, composite slabs, steel structures

Денис ПОПОВСКИ[1], Петар ЦВЕТАНОВСКИ[2], Миле ПАРТИКОВ[3]

ЕФЕКТИТЕ ОД ПРЕДНАПРЕГАЊЕ СО СПУШТАЊЕ НА ПОТПОРА КАЈ КОНТИНУИРАНИ СПРЕГНАТИ НОСАЧИ

РЕЗИМЕ

Ефектите од преднапрегањето на спрегната континуирана греда преку спуштање на средната потпора се неспоредливи. Испитувањето на овие ефекти претставува едно од главните цели на едно комплексно експериментално и теориско истражување на спрегнати континуирани носачи. Во ова соопштение дадени се методите на истражување на две исти спрегнати греди, каде на едната е извршено преднапрегање. Исто така, дадени се и резултатите од испитувањето како и од теориското истражување на аналитички модели, вклучувајќи ги и компаративната анализа на двете спрегнати греди.

Клучни зборови: спрегнати конструкци,, спрегнати плочи, челични конструкции

[1] Assist. MSc, Faculty of Civil Engineering, University “Ss. Cyril and Methodius”, Skopje, Republic of Macedonia, popovski@gf.ukim.edu.mk
[2] Prof. PhD, Faculty of Civil Engineering, University “Ss. Cyril and Methodius”, Skopje, Republic of Macedonia, cvetanovski@gf.ukim.edu.mk
[3] Assist. MSc, Faculty of Civil Engineering, University “Ss. Cyril and Methodius”, Skopje, Republic of Macedonia, partikov@gf.ukim.edu.mk

1. METHOD OF TESTING

1.1. Testing model

The testing was performed on two continuous composite (steel and concrete) beams. The beams are with the same cross section composed from the same elements with the same class of material. The cross section of the beams is composed from *IPE270* as the steel main beam, with steel sheeting from *Bondeck 600 (thickness of 1.0mm)* with ribs transverse to the length of the main beam, creating T-beam. The steel sheeting is connected to the beam with headed stud shear connectors, in two columns longitudinal to the main beam. The studs are thru deck welded to the beam in accordance with EN 14555. The full thickness of the concrete beam is *52+58=110mm*, shown in figure 1. The concrete is reinforced with *Q283 (Ø6/100mm)* class B reinforcement, where above the middle support of the beam, the concrete is reinforced with two layers of the same reinforcement. The composite beam is continuous with two spans of 5750mm with total length of 11500mm.

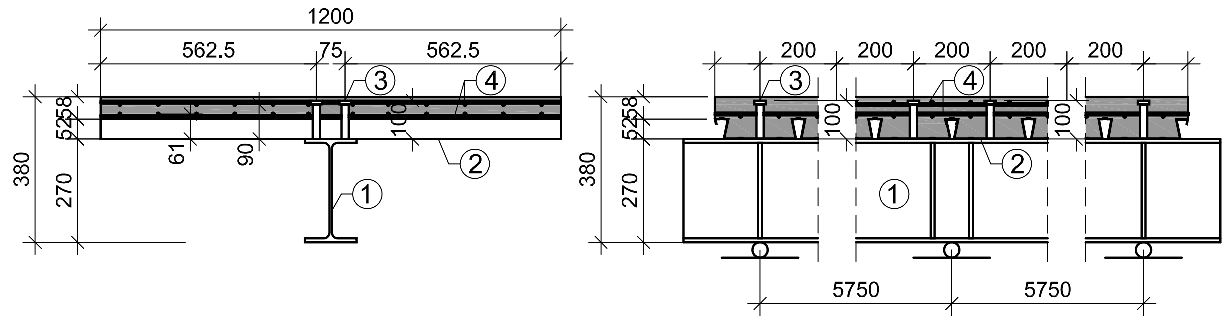

Figure 1. Testing model

Where:

1) main beam *IPE270 (S275JR)*
2) steel sheeting *Bondeck 600, t=1.0mm (S550GD Z275)*
3) Nelson headed stud, *d=19mm, hsc=100mm (S235J2+C450)*
4) reinforcement *Q273 (Ø6/100mm)* class B *(f_y/f_u=600/660)*

1.2. Measuring and loading equipment

In figure 2 the disposition of the measuring and loading equipment is shown, where *DM1* and *DM2* are dynamometers for controlling the applied force thru the 100 ton presses. Electronic comparators *U1* to *U6* are placed for measuring the deformation of the beam. *U4* and *U5* are dial comparators for measuring the slip between the steel beam and the concrete slab. *D11* to *D34* are measuring points for deformter with main base with 250mm length. *B1* to *B7* are strain gauges *Kyowa* with 120mm length for the concrete, where AC11 to AC303 are strain gauges *Kyowa* with 5mm length for the steel, and *A11* to *A24* are strain gauges with 5mm length for the reinforcement.

The load is applied thru the 100 ton presses, transferred thru the primary transmission beams *TL* and *TD*, then thru the secondary transmission beams *T1* to *T4*, where from two applied forces eight longitudinal disturbed forces are obtained.

1.3. Method of testing

The first composite (concrete and steel) beam is loaded with cycled load up to 40kN in dynamometer, then the load is applied in subsequent increments until failure occurs (up to 450kN). After every step of loading, values from the measuring equipment (deformeter and dial comparators) are obtained. From the electronic dynamometers, comparators and strain gauges the measurements are obtained in real time throughout the whole testing.

The second composite beam is same as the first one, with one difference only, the beam is pre-stressed by imposed controlled deformation with lowering the middle support by 18mm. The method of testing after the pre-stressing is the same as with the first beam.

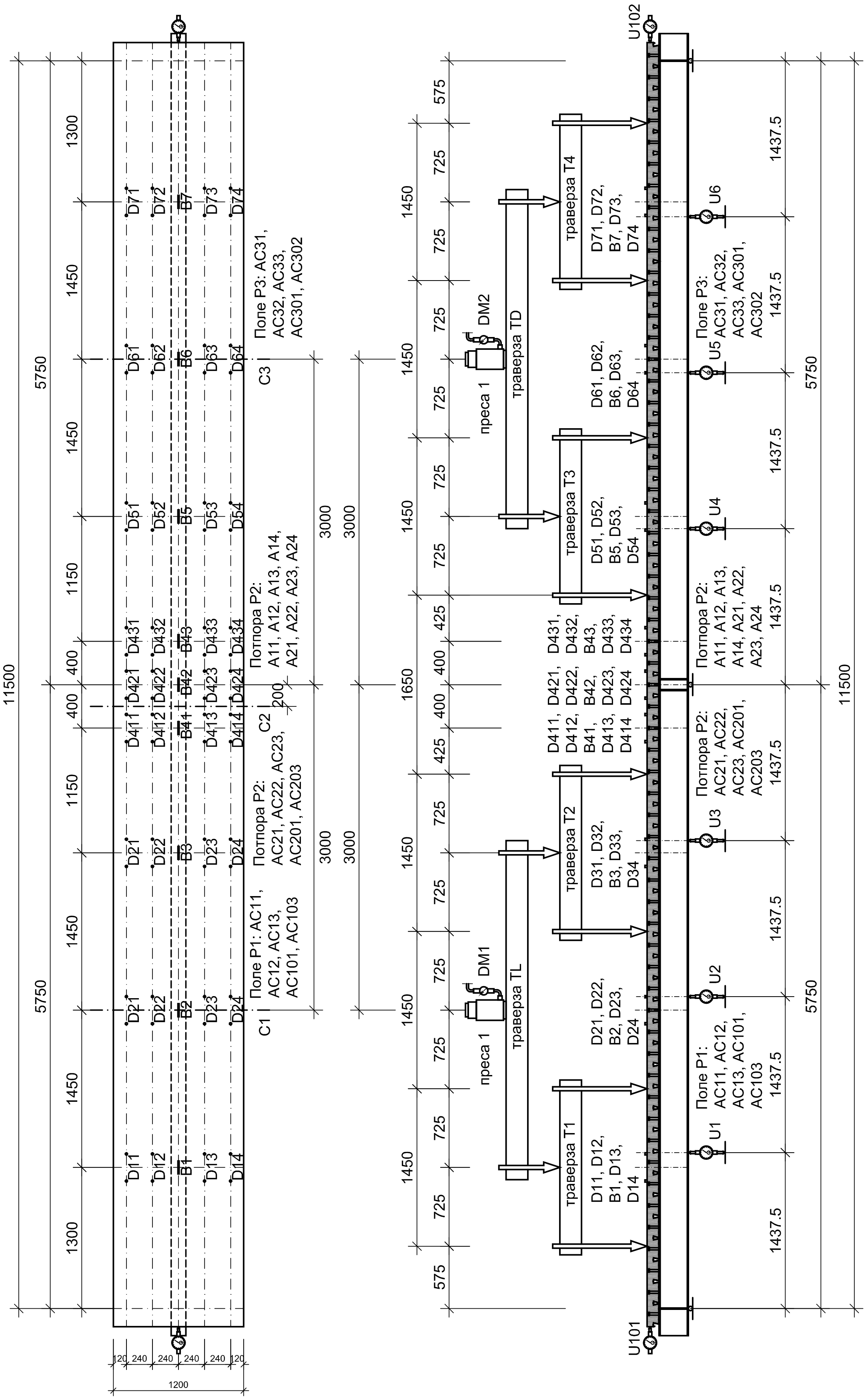

Figure 2. Disposition of the testing equipment

The second beam is placed with elevation on the middle support for 18mm, and in that position the placing of the steel sheeting, the welding of the studs and the concreting was made. After 32 days preparation and installation of the measuring and loading equipment, the beam was pre-stressed by imposed controlled deformation. After the readings from the measuring equipment at this step, the cycling load up to 40kN was imposed, and then the load is applied in subsequent increments until failure (up to 600kN).

Realistic 3D models, created with 3D solid elements and with usage of nonlinear behavior of links with defined characteristics of the used materials and elements, in SAP2000 software were used for comparative analysis of the testing. Also, a model for comparative analysis for the tested beams was used in accordance with EN 1994, using frame elements with pushover analysis for obtaining only the internal forces.

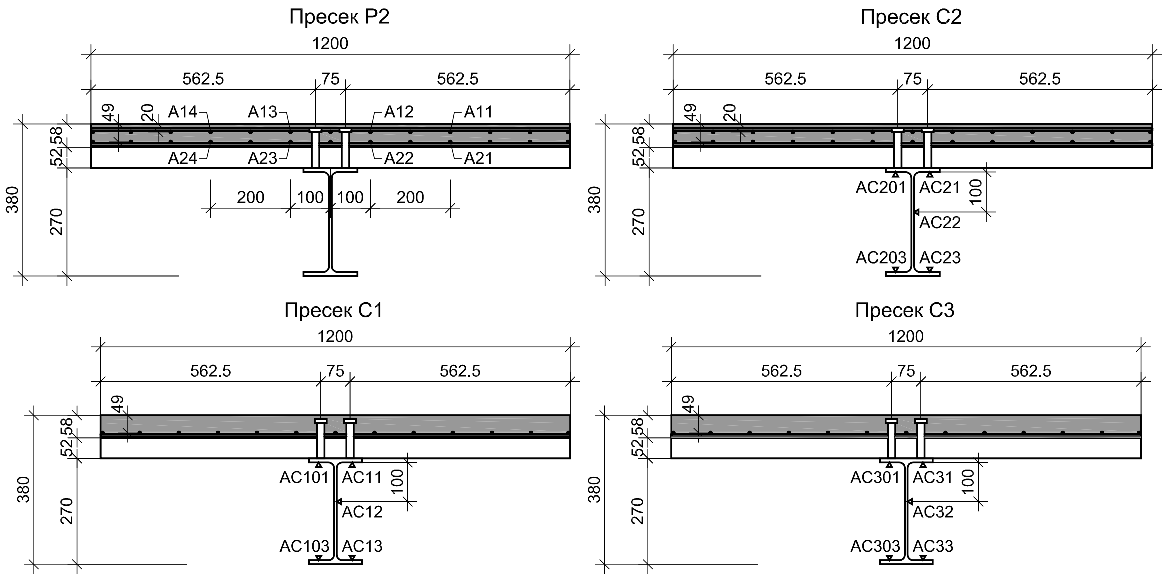

Figure 3. Strain gauges placement at characteristic cross sections

In figure 3 the placement of the strain gauges at the characteristic cross sections is shown. Also, the placement of the elements of the cross section (studs, reinforcement) are shown.

2. TESTING THE MATERIALS

The materials were tested for obtaining the real mechanical characteristics for the need of the testing of the two main beams. Previously, the behavior of the shear connectors was tested on three modified (specific) samples.

2.1. Testing the characteristics of the concrete

After every casting of the concrete a sample was taken for testing the strength of cubes with dimensions 150x150x150mm, and cylinders with dimensions 150x300mm. The modulus of elasticity was tested on three cylinders for each casting. Also, the shrinkage of each cast concrete is measured with three prisms within 175 days for the first beam, and 157 days for the second beam. The adapted strength class of concrete for the two beams is C25/30 according to EN 1992.

The testing of the compression and tensile strength of the concrete for the first beam was made on the 29th and the 32nd day from casting. The compression strength of cube is $f_{ck,cube}=36.64MPa$ (+22.1%), the strength of cylinder is $f_{ck}=29.51MPa$ (+18.0%). The tensile strength of the concrete for the first beam is $f_{cm}=2.95MPa$ (+13.5%), and the modulus of elasticity is $E_{cm}=31.97GPa$ (+3.1%). The shrinkage at the 29th day (the day for the testing of the first beam after the casting) is measured with value of 0.255‰. The calculated value of the shrinkage in accordance with EN 1992 is 0.230‰ (-10.9%).

For the second (pre-stressed) beam, the obtained values from the testing of the concrete are $f_{ck,cube}=32.03MPa$ (+6.8%, with standard deviation of σ=1.79), $f_{ck}=31.65MPa$ (+26.6%), $f_{cm}=2.97MPa$ (+14.2%) and $E_{cm}=31.65GPa$ (+2.1%). The measured shrinkage on the 34th day (the day for the testing of the second beam after the casting) is 0.241‰. The calculated value of the shrinkage in accordance with EN 1992 is 0.273‰ (+13.3%).

2.2. Testing the characteristics of the steel

The yield strength, the tensile strength and the maximum elongation of a representative sample of the shear connector material, steel beam, reinforcement and steel sheeting is determined.

The reinforcement steel is class B, in accordance with EN 1992-1-1, Annex C, table C.1 and C.3N, with yield strength of $f_{yk}=597N/mm^2$, tensile strength $f_{uk}=662N/mm^2$, with $k=f_{uk}/f_{yk}=1.11$, and $\varepsilon_{uk}=9.9\%$.

The steel for the headed studs is class S235J2+C450, in accordance with EN 13918, with yield strength $f_y=502N/mm^2$, tensile strength $f_u=552N/mm^2$, with $k=f_u/f_y=1.10$ and $\delta_5=18.5\%$.

The steel for the steel sheeting deck is class S550GD Z275, in accordance with EN 10147, with yield strength $f_y=675N/mm^2$, tensile strength $f_u=770N/mm^2$, with $k=f_u/f_y=1.14$ and $\delta=24.6\%$.

The steel for the beam is S275JR, in accordance with EN 1993, with yield strength $f_y=275N/mm^2$, tensile strength $f_u=424N/mm^2$, with $k=f_u/f_y=1.54$ and $\varepsilon_u=18.9\%$.

The results from the testing of the steel (reinforcement, headed suds, steel sheeting and steel beam) meet the requirements from EN 1992 and EN 1993.

The same class of the steel for reinforcement, headed studs, steel sheeting and beam is used for the two composite continuous beams.

3. RESULTS FROM THE TESTING

The results from the testing are shown for each composite beam separately, "*ГН1*" and "*ГН2*" as the pre-stressed beam, with comparison with the tridimensional analytical model "*AM*" and the analysis according to EN 1994, Eurocode 4 "*EC4*". *P1* (first span), *P2* (middle support) and *P3* (second span) are points of interest (measuring points) on characteristic placements of the tested beams, according to figure 2.

3.1. Composite, steel and concrete, continuous beam

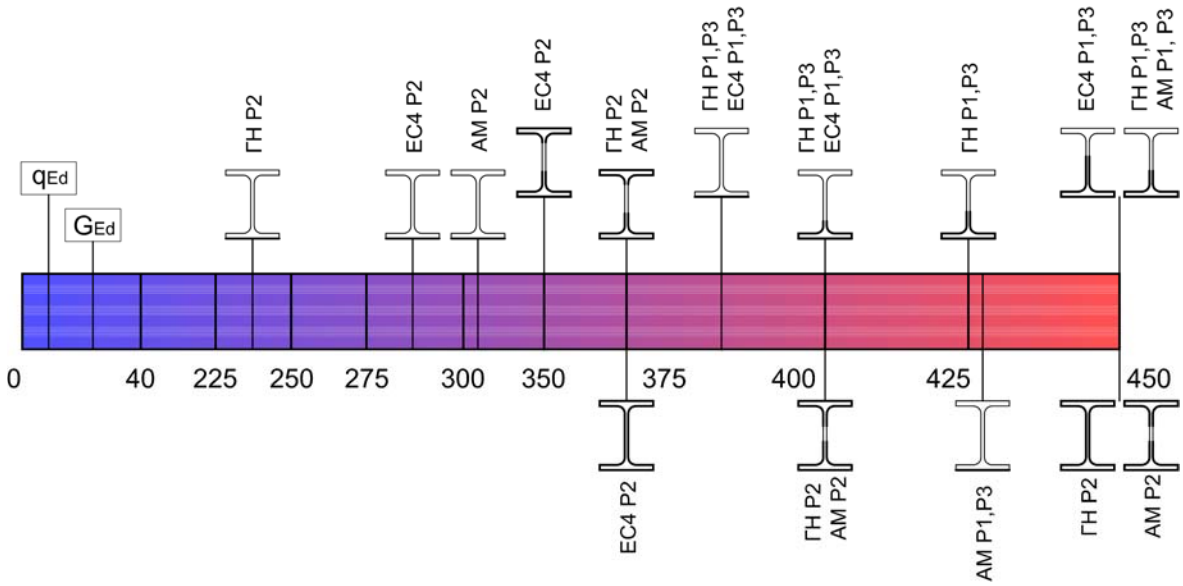

Figure 4. Display of the results from the testing of "ГН1"

In figure 4 the results from the testing and the analytical research of the first composite continuous beam is shown, where can be seen the elastic and plastic behavior of the composite beam. For instance, the first crack in the concrete is on applied load in dynamometer with value of 60kN. In loading between 225kN and 250kN the most exposed fiber (at the support) of "*ГН1*" reached the yield strength of the cross section. The same happens for the model analyzed in accordance with EN 1994 between 275kN and 300kN, and for "*AM*" just over 300kN.

First full plastification of the steel cross section is at support for the model analyzed according to EN 1994 at step of loading of 375kN in dynamometer. Full plastification of the same cross section is at step of loading of 450kN for "*ГН1*", and for "*AM*" just over 450kN. At the last step of loading (450kN in dynamometer) only the lower flange is plastificated for all analyzed and tested composite beams at the span (*P1* and *P3*).

The difference in the deformations between the analyzed and tested beams are given in figure 5. The smallest value of the elastic deflection is from the analyzed model according to EN 1994, $\delta_{EC4}=10.06mm$ then $\delta_{AM}=10.73mm$ (+6.7%) and $\delta_{ГН}=12.14mm$ (+20.6% from "*EC4*", +13.14% from "*AM*"). For the deflection with plastic behavior of the beam, the measured value for "*AM*" is $\delta_{AM}=23.20mm$ and for "*ГН1*" is $\delta_{ГН}=24.41mm$ (+5.2%).

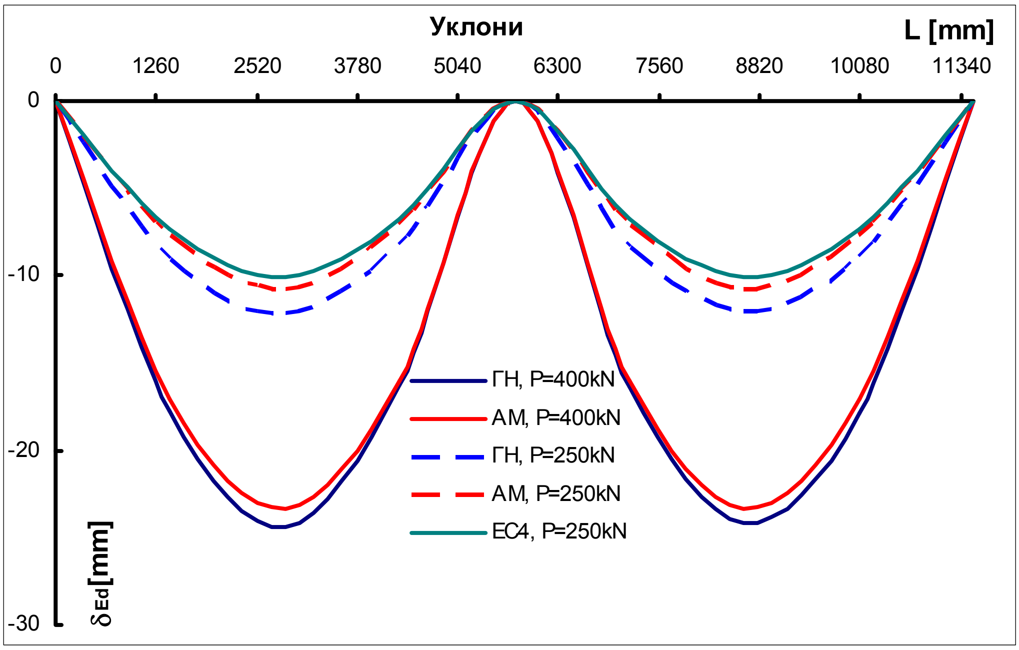

Figure 5. Deformations of "ГН1"

From the research of the composite (steel and concrete) continuous beam, the analyzed model "*EC4*" is with the smallest ultimate limit state, with moment at the support $M_{Ed,EC4}=187.06kNm$, then is the tested model "*ГН1*" with moment at the support $M_{Ed,ГН}=234.12kNm$ (+25.2%), and for "*AM*" the moment at the support is $M_{Ed,AM}=254.50kNm$ (+36.1% from "*EC4*", +8.7% from "*ГН*").

At the final step of loading value of 450kN, the internal forces at the researched beams at spans *P1* and *P3* are $M_{Ed,EC4}=232.77kNm$ for "*EC4*", $M_{Ed,ГН}=221.19kNm$ (-5.0%) for "*ГН1*" and $M_{Ed,AM}=206.05kNm$ (-11.5% from "*EC4*", -6.8% from "*ГН1*").

The diagrams of the internal forces - moments are given in figure 6, for the tested beam and for the analyzed composite beams. For comparison purposes, additional moment diagram is displayed. The moment diagram "*MK*" is for continuous beam with constant stiffness with the same spans load as the researched beams for load value on dynamometer of 450kN.

The measured residual deflection after the unloading of the beam from the full load is $\delta_{PL}=7.93mm$ in span *P1* and $\delta_{PL}=7.87mm$ in span *P3*.

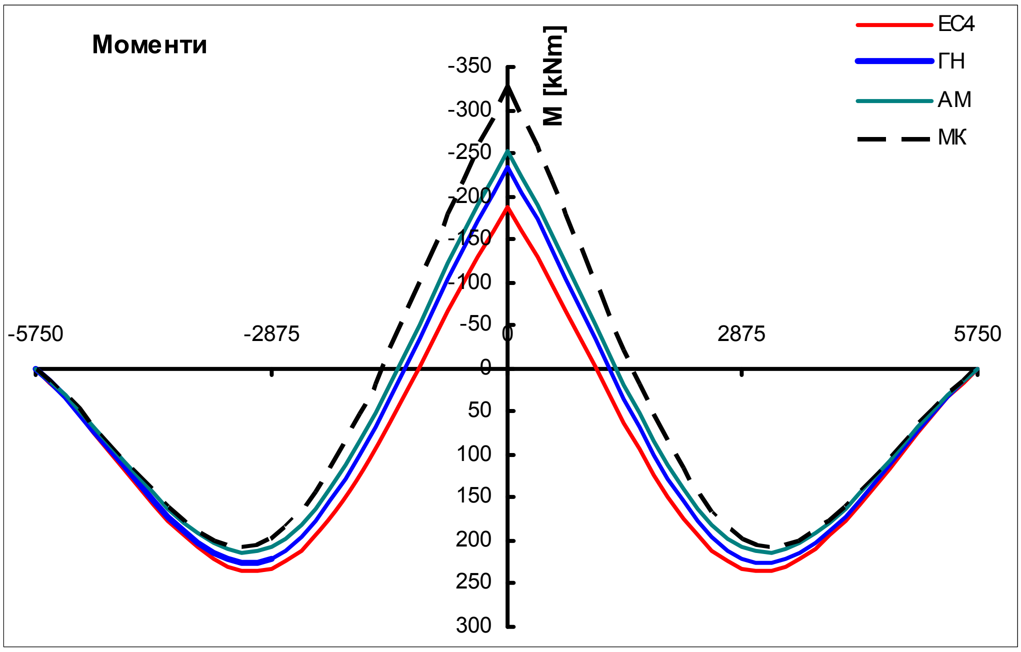

Figure 6. Internal force - moments for “*ГН1*”

3.2. Pre-stressed composite, steel and concrete, continuous beam

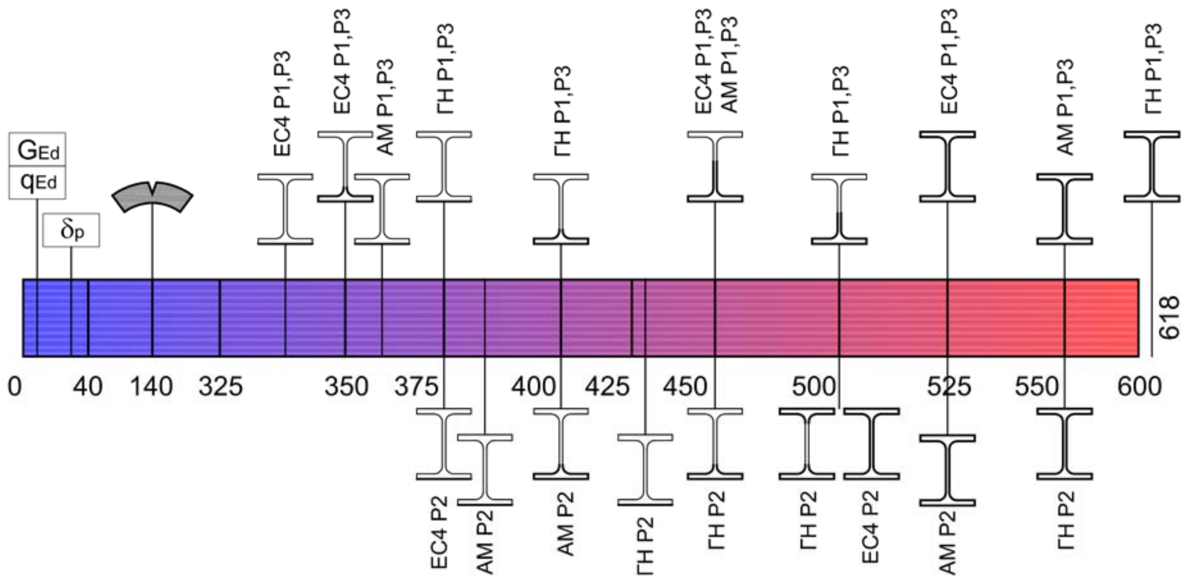

Figure 7. Display of the results from the testing of “ГН2”

Following the logic from the previous chapter, the results of the pre-stressed composite beams are given in figure 7, where the first crack in the concrete appears at the load step of 140kN on dynamometer. The emergence of the cracking of the concrete is delayed for 80kN in dynamometer.

The full plastification of the cross section at the support is for “*EC4*” at the step of loading of 500kN. The full plastification of the same cross section for “*AM*” is at the step of loading of 525kN, where at the same step the full plastification occurs for the cross sections at P1 and P3 for “*EC4*”. At the step of loading of 525kN the full plastificcation occurs for “*AM*” at P1 and P3, and at the same time for “*ГН2*” at the middle support. The full plastificationat spans P1 and P3 for “*ГН2*”occurs at step of loading of 618kN in dynamometer.

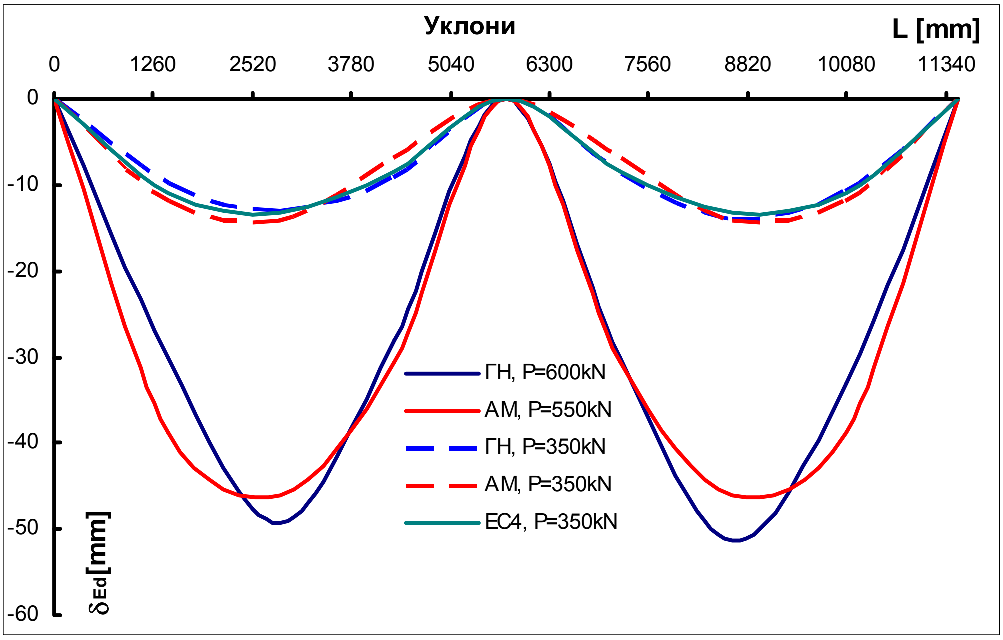

Figure 8. Deformations of "ГН2"

The difference in the deformations between the analyzed and tested beams are given in figure 8. The value of the elastic deflection from the analyzed model according to EN 1994 is $\delta_{EC4}=13.18mm$, then $\delta_{AM}=14.06mm$ (+6.7%) and measured value for "*ГН2*" is $\delta_{ГН}=13.04mm$ (-1.1% from "*EC4*", -7.3% from "*AM*"). For the deflection with plastic behavior of the beam, the measured value for "*AM*" is $\delta_{AM}=46.13mm$ and for "*ГН2*" is $\delta_{ГН}=51.32mm$ (+11.3%).

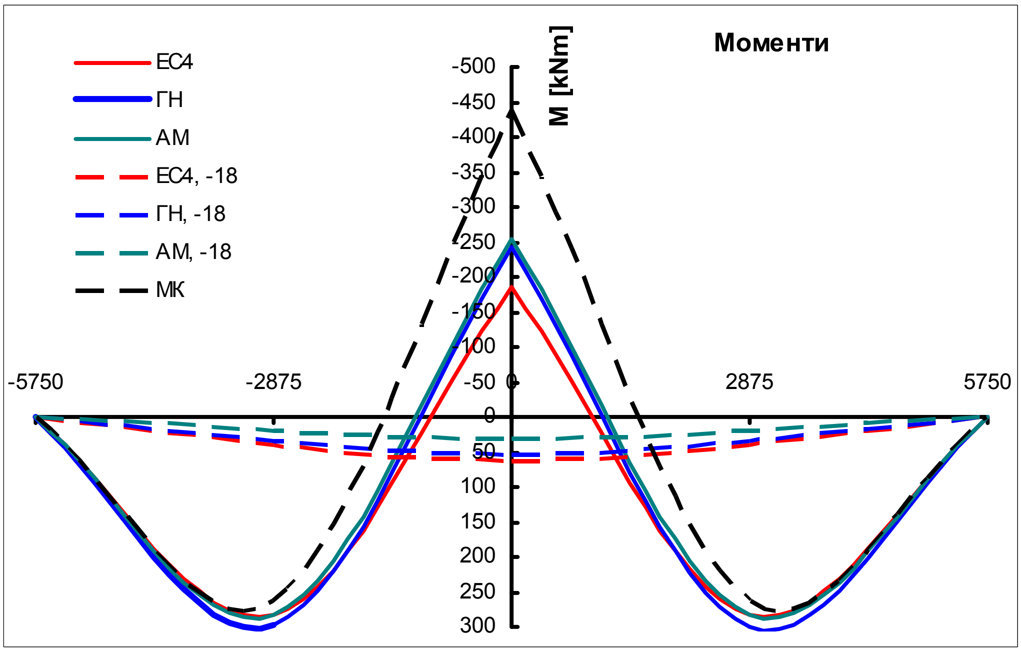

Figure 9. Internal force - moments for "*ГН1*"

The moment at the support according to EN 1994 is $M_{Ed,EC4}=187.06kNm$, for the tested model "*ГН2*" the moment is $M_{Ed,ГН}=244.13kNm$ (+30.5%), and for "*AM*" the moment at the support is $M_{Ed,AM}=254.60kNm$ (+36.1% from "*EC4*", +4.3% from "*ГН2*").

At the final step of loading for the each researched beam, the internal forces at spans *P1* and *P3* are $M_{Ed,EC4}=282.78kNm$ for “*EC4*”, $M_{Ed,\Gamma H}=297.30kNm$ (+5.1%) for “*ΓH2*” and $M_{Ed,AM}=284.60kNm$ (+0.65% from “*EC4*”, -4.27% from “*ΓH2*”).

For comparison purposes additional moment diagram is displayed, “*MK*” is for continuous beam with constant stiffness with the same spans load as the researched beams for load value on dynamometer of 600kN.

The measured residual deflection after the unloading of the beam from the full load is $\delta_{PL}=25.32mm$ in span *P1* and $\delta_{PL}=25.55mm$ in span *P3*.

4. ANALYSIS OF THE RESULTS

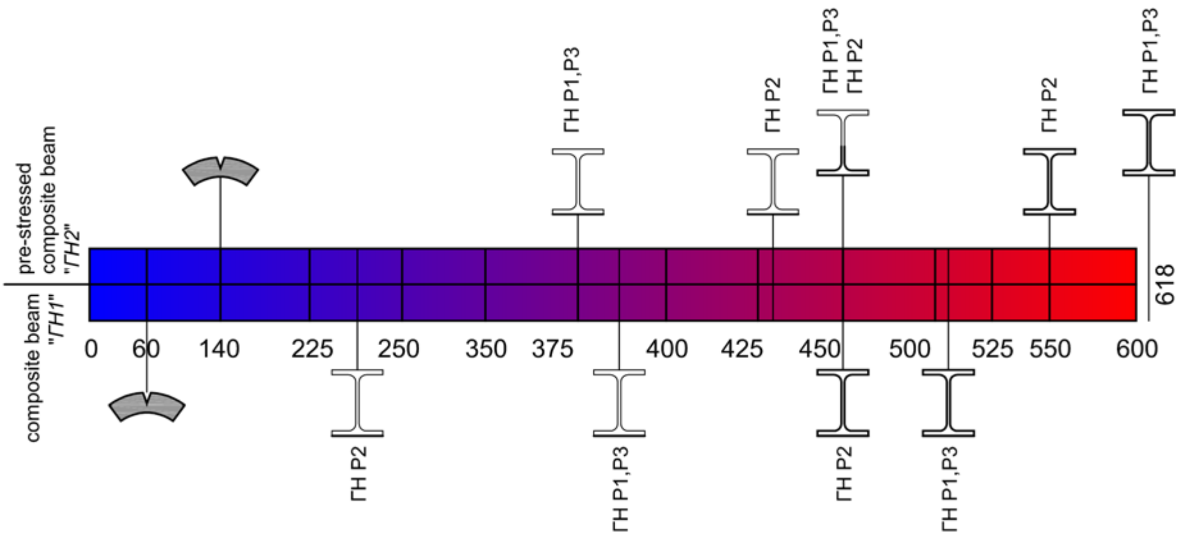

Figure 10. Comparison between the tested beams

In figure 10 the different behavior of the two composite (steel and concrete) tested beam are shown, and it can be seen that the pre-stressed composite beam “*ΓH2*” has advantages compared to “*ΓH1*”.

At first, the cracking of the concrete is delayed for 80kN in dynamometer, which is great advantage for serviceability limit state of the structure and for the elastic behavior of the beam. According to the placement of the loading equipment shown in figure 2, the difference in the loading is about 15.4kN/m’. Also the full plastification of “*ΓH1*”at the middle support is at 450kN, where for “*ΓH2*” is at 550kN (+22.2%), where the difference in loading is about 19.3kN/m’. The approximate plastic capacity of the composite beam at the span (P1 and P3) is at loading step of 512kN in dynamometer, where the plastic capacity of the same cross section for the pre-stressed composite beam is at loading step of 618kN (+20.7%), with difference in loading about 20.5kN/m’.

The measured values for the last step of loading for “*ΓH1*” (450kN) is 24.41mm, where for “*ΓH2*” at the same step of loading is 20.12mm (-17.6%).

5. CONCLUSIONS

Having the results from the testing of the two composite (steel and concrete) continuous beam, and with the analysis of the results, some conclusions can be drawn.

There are obvious advantages of the pre-stressed composite beam. One of the advantages is the bigger serviceability limit state of “*ΓH2*” compared to “*ΓH1*”, where the pre-stressed composite beam can be load with additional 15.4kN/m’ until the first crack in the concrete at the middle support occurs.

In the elastic behavior of the beam, the advantages are 2.33 times higher bearing capacity than the composite beam “*ΓH1*” until the cracking of the concrete occurs at the middle support (loading value in dynamometer from 60kN to 140kN). There is also 1.88 times higher bearing capacity after the cracks occurs until the yield strength of the most exposed fiber is reached. The pre-stressed composite beam "*ГН2*" has 20.7% (20.5kN/m') higher ultimate limit state than the composite beam "*ГН2*", which means that the pre-stressed beam can be load with additional 20.5kN/m' until the ultimate limit state is reached. Also, the deflection of the pre-stressed composite beam is for 17.6% lesser.

It can be concluded that with pre-stressing the composite beam, by controlled imposed deformation (deflection of the middle support) by 18mm, there are many advantages of the behavior of the beam compared to (ordinary) composite beam.

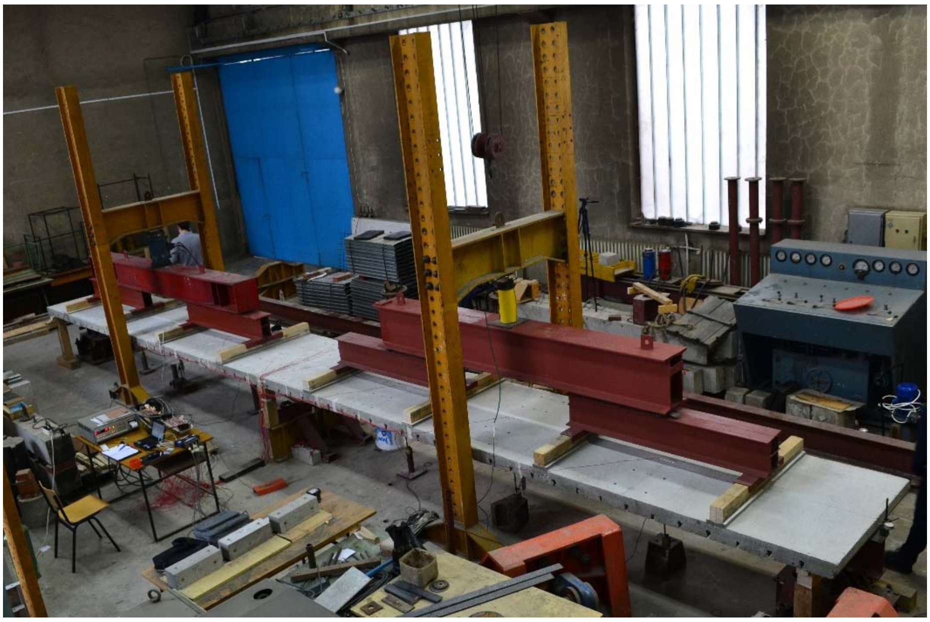

Figure 11. Composite beam subjected to the testing

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