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# TESTING THE BEHAVIOR OF CONTINUOUS COMPOSITE BEAM PRE-STRESSED BY CONTROLLED IMPOSED DEFORMATIONS

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The composite steel and concrete structures are complex unity of the two most utilized materials in structural engineering. The analysis of such structures requires knowledge of the characteristics and behavior of both materials, and of the structures as a whole. To have a real picture of the realistic behavior, there is need for research, which represent the core knowledge in the modern civil engineering. These kind of structural elements have nonlinear behavior even within the lower values of the ultimate loading. In order to obtain further data on the effects of composite steel and concrete structures for continuous beams, an experimental program was made with multiple elements and beams. In this paper the results of the testing of the behavior of continuous composite beam pre-stressed by controlled imposed deformation are presented, compared with the analysis in accordance with EN1994, and with complex, realistic 3D structural model, created in SAP2000.

**Keywords:** composite structures, composite slabs, steel structures

## TESTING MODEL

The cross section of the beam 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, where the longitudinal distance between the studs is *200mm*. The studs are thru deck welded to the beam in accordance with EN14555. The full thickness of the concrete beam is *52+58=110mm*, as 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*. The full height of the cross section is *270+110=380mm*.

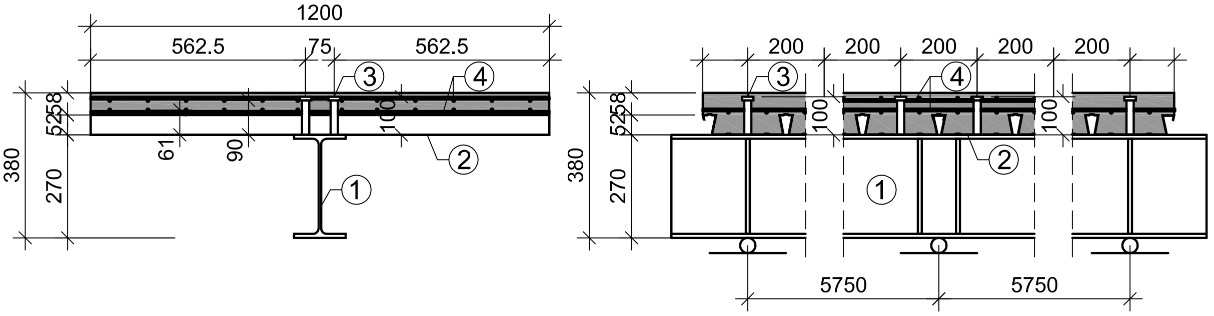


**Figure 1**. Testing model

Where:

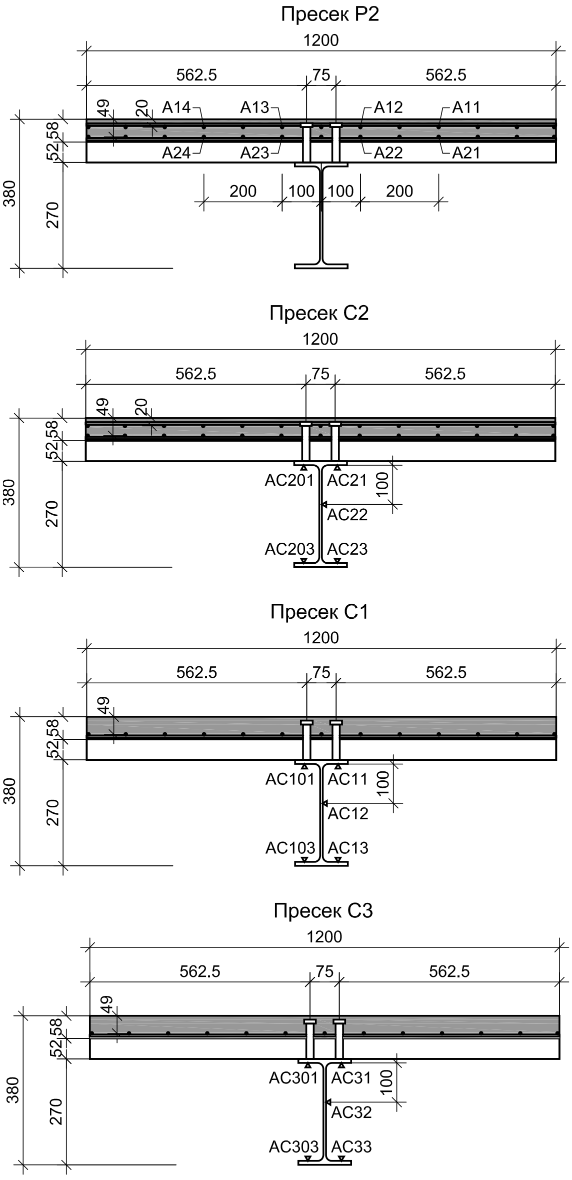
1) main beam *IPE270 (S275JR)*
2) steel sheeting *Bondeck 600, t=1.0mm (S550GD Z275)*
3) Nelson headed stud, *d=19mm, hsc=100mm (S235J2+C450)*
4) reinforcement *Q273 (Ø6/100mm)* class B *($f_y/f_u$=600/660)*

## MEASURING AND LOADING EQUIPMENT

The spans are divided in three measuring points for displacements, measured by electronic comparators *U1* to *U6*, as shown in figure 3. The electronic comparators are connected to HBM Quantum data acquisition system, where the displacements are obtained in real time throughout all of the loading phases. Dial comparators *U101* and *U102* are used for measuring the slip between the steel beam and concrete slab.

There are three measuring points in each span for strains on the top face of the concrete slab. The strains are measured with dial deformeter with main base of 200mm, *D11* to *D24*, and *D51* to *D71* for strains at the spans. For strains measured at the middle support, the measuring points are *D411* to *D434*. Additionally at the middle of the concrete slab, longitudinal to the length of the beam, at the position of the measuring points, strain gauges for concrete are used, with base length of 120mm. *B1* to *B3*, and *B5* to *B7* are strain gauges for concrete at the spans, *B41* to *B43* are strain gauges at the middle support.

There are, also, measuring points for strains in the steel section. The strains are obtained with usage of strain gauges with base length of 5mm, placed at the maximum moments in the spans and at the support. *AC11* to *AC103*, and *AC31* to *AC302* are strain gauges for the steel section at the maximum moment in the spans. *AC21* to *AC203* are strain gauges for the steel section at the support. Additionally, strain gauges for the reinforcement at the support are used, *A11* to *A24*. The strain gauges for the reinforcement are with base length of 5mm.


Пресек P2

Пресек C2

Пресек C1

Пресек C3

**Figure 2**. Strain gauges placement at characteristic cross sections

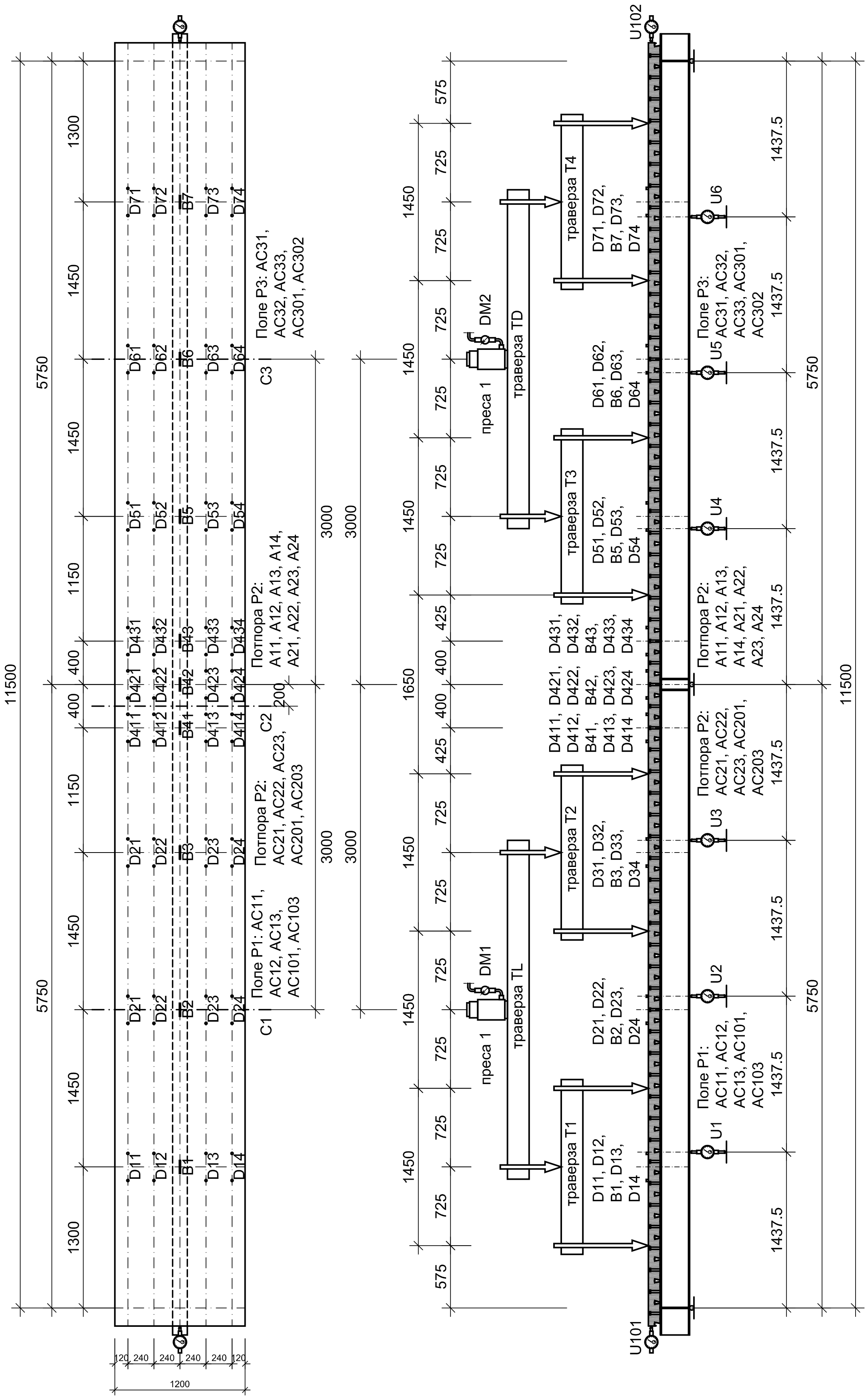


**Figure 3**. Disposition of the testing equipment

strain gauges are manufactured by *Kyowa*, and connected to HBM Universal amplifier, where the results are obtained at the end of each loading step. The placement of the strain gauges at the characteristic cross sections are given in figure 2.

Each of the loading steps are applied through two 100 ton presses, transferred by the primary transmission beams *TL* and *TD*, where through the secondary transmission beams *T1* to *T4*, the load is additionally disturbed. With the usage of the two layers of transmission beams, from two applied forces, eight longitudinal disturbed forces are obtained. The value of the load is controlled with the help of dynamometers at each press, connected to HBM Quantum data acquisition system, with monitoring (and obtaining) the value of the load in real time.

## METHOD OF TESTING

The composite beam is pre-stressed by imposed controlled deformation with lowering the middle support by 18mm. The steel beam is set with elevation on the middle support from 18mm, and in that position the installation of the sheeting, the welding of the studs an the concreting of the slab were made. After 32 days preparation and installation of the measuring and loading equipment, the beam was pre-stressed by imposed controlled deformation. After obtaining the results from the measuring equipment at this step, the cycling load up to 40kN (on one dynamometer) was imposed, after 5 cycles, the load was applied in subsequent increments until failure occurs (up to 600kN on one dynamometer).

For comparative analysis of the testing realistic 3D models in SAP2000 software were created, using 3D solid elements and with nonlinear behavior of links with defined characteristics of the used materials and elements.

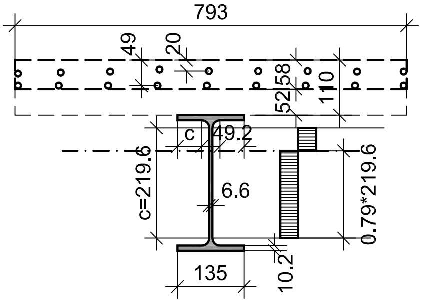


**Figure 4**. The effective cross section at support

Also, another model was used in accordance with EN1994, using frame elements with pushover analysis for obtaining only the internal forces. The frame model is with different effective cross sections longitudinal to the length of the composite beam.

## TESTING THE MATERIALS

After the 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 157 days. The adapted strength class of concrete for the beam 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 32nd day from casting. The compression strength of cube is $f_{ck,cube}=32.03MPa$ (+6.8%, with standard deviation of $\sigma$=1.79), the strength of cylinder is $f_{ck}=31.65MPa$ (+26.6%). The tensile strength of the concrete is $f_{cm}=2.97MPa$ (+14.2%), and the modulus of elasticity is $E_{cm}=31.65GPa$ (+2.1%). The shrinkage at the 32nd day (the day for the testing after the casting) is measured with value of 0.241‰. The calculated value of the shrinkage in accordance with EN 1992 is 0.273‰ (+13.3%).

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 studs, steel sheeting and steel beam) meet the requirements from EN 1992 and EN 1993.

**Figure 5**. Composite beam subjected to the testing

## RESULTS FROM THE TESTING

The measured data and results from the measuring and loading equipment were obtained and adequately processed.

Figure 6 shows the measured strains in the steel section at the support, where the effects of the pre-stressing are evident.

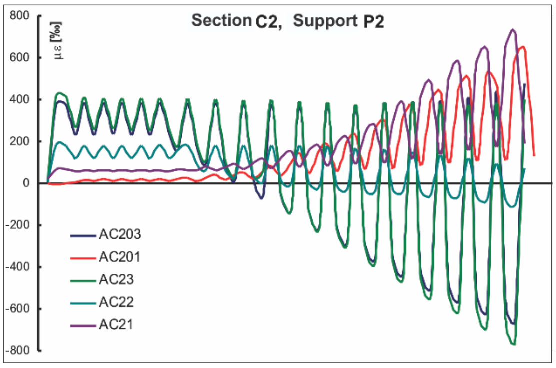


**Figure 6**. Measured strains in the steel section

It is evident that the cross section at the support, from the effects of the pre-stressing is tensioned, and with the increase of the loading it becomes compressed.

At the span, at the maximum measured moment, the cross section is negligible compressed, which does not affect the overall bearing capacity of the beam.

Figure 7 shows the measured strains in the reinforcement at the support. It is evident that the effects of the pre-stressing are with little impact, the reason is activation in compression of the concrete slab from the pre-stressing.

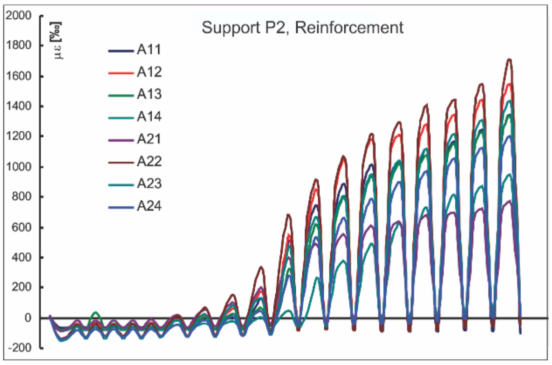


**Figure 7**. Measured strains in reinforcement

The processed results are compared with the results obtained from the analytical research of the composite pre-stressed beam in accordance with EN 1994. Comparison between the measured and calculated results, also were made with the realistic 3D model.

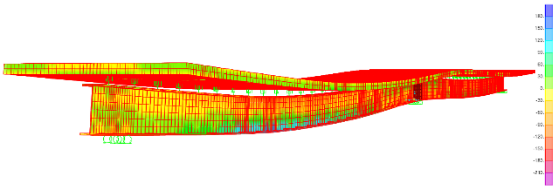


**Figure 8**. 3D realistic model

In figure 9 the results from the testing and the analytical research of the pre-stressed composite continuous beam is shown, where the elastic and plastic behavior of the composite beam can be seen. For instance, the first crack in the concrete is on applied load in dynamometer with value of 140kN. In loading of 375kN the most exposed fiber (at the span) of the tested beam “ΓH” reached the yield strength of the cross section. The same happens for the model analyzed in accordance with EN 1994 “EC4”between 3250kN and 350kN, and for the analytical 3D model “AM” at 350kN in dynamometer.

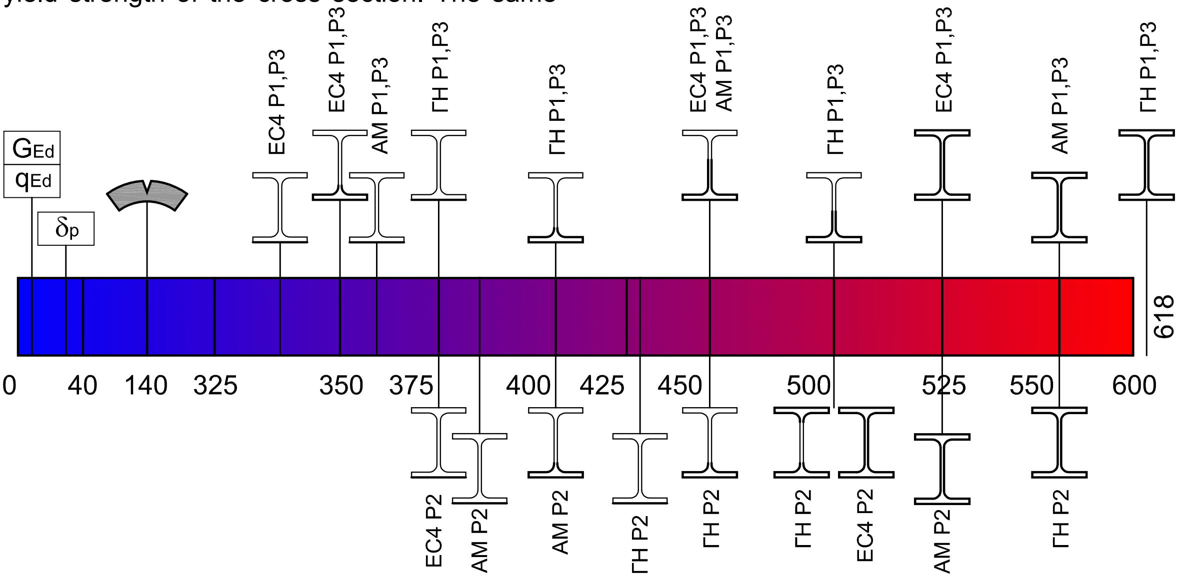


**Figure 9**. Display of the results from the research

First full plastification of the steel cross section, where the ultimate limit state is reached, is at the support for the model analyzed in accordance with EN 1994 “EC4” at the step of loading of 500kN. The full plastification of the same cross section is at step of loading of 525kN for the analytical 3D model “AM”, where the ultimate limit state for the cross sections at P1 and P3 for “EC4” occurs. At the step of loading of 550kN the full plasstification occurs for “AM” at P1 and P3, and at the same time for “ΓH” at the middle support. The ultimate limit state is reached at spans P1 and P3 for “ΓH” occurs at step of loading of 618kN in dynamometer.

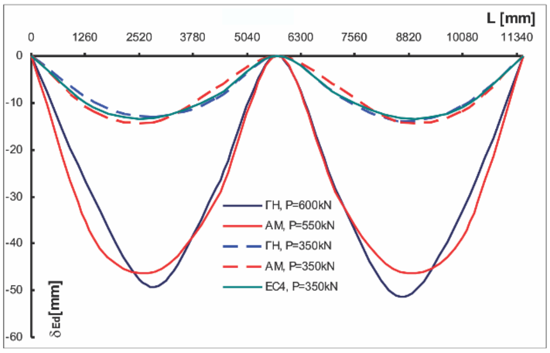


**Figure 10**. Measured and analyzed deformations

The difference in the deformations between the analyzed and tested beams are given in figure 10. 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 “ΓH” is $\delta_{ΓH}$=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 “ΓH2 is $\delta_{ΓH}$=51.32mm (+11.3%). 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.

The diagrams of the internal forces - moments are given in figure 11, 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 600kN. The moment at the support according to EN 1994 is $M_{Ed,EC4}$=187.06kNm, for the tested model “ΓH” the moment is $M_{Ed,ΓH}$=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 “ΓH”). 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”, $M_{Ed,ΓH}$=297.30kNm (+5.1%) for “ΓH” and $M_{Ed,AM}$=284.60kNm (+0.65% from “EC4”, -4.27% from “ΓH”).

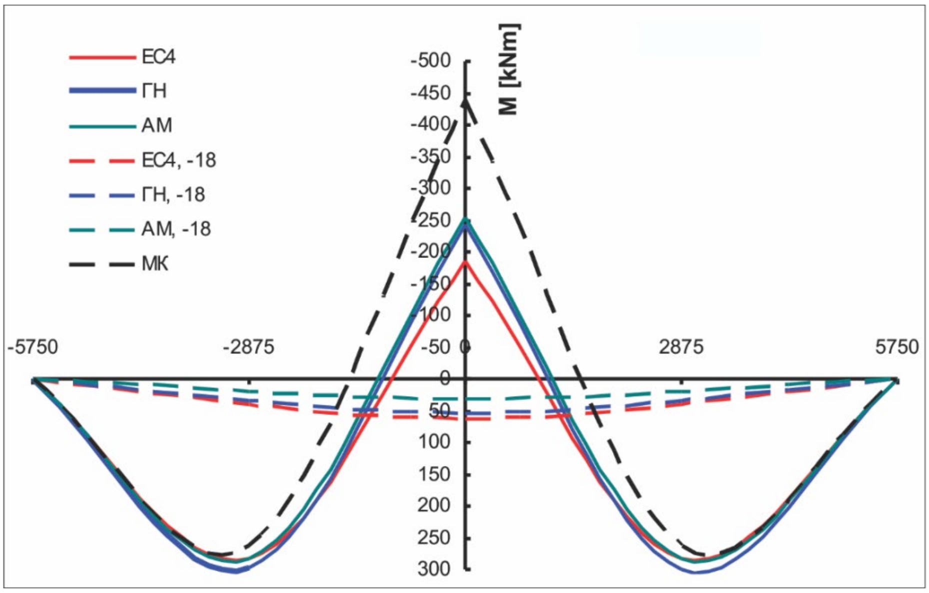


**Figure 11**. Internal force – moments

## CONCLUSION

From the experimental and analytical analyses of the pre-stressed continuous composite beam, the following conclusions can be drawn:

- Pre-stressing by imposed controlled deformation of the continuous composite beam have significant influence on the behavior and the redistribution of the moments.
- The emergence of the cracking of the concrete at the support is delayed because of the compression in the concrete slab due the pre-stressing.
- The pre-stressing by controlled imposed deformation of the composite beam increase the bearing capacity of the beam.
- The analysis according to EN 1994 gives results with smaller bearing capacity due the strict value of $\psi_L$=1.5 for pre-stressing by imposed deformation.

## REFERENCES

[1] Popovski D., Experimental and theoretical research of the effects of composite steel and concrete structures from continuous beams, doctoral dissertation, 06.2015, Faculty of civil engineering in Skopje, UKIM, Skopje, R. Macedonia.

[2] European Standard EN 1994, Eurocode 4: Design of composite steel and concrete structures, Part 1-1: General rules and rules for buildings, 12.2004, +AC 04.2009, European Committee for Standardization.

[3] European Standard EN 1993, Eurocode 3: Design of steel structures, Part 1-1: General rules and rules for buildings, 03.2005, +AC 06.2009, European Committee for Standardization.

[4] European Standard EN 1992, Eurocode 2: Design of concrete structures, Part 1-1: General rules and rules for buildings, 12.2004, European Committee for Standardization.

[5] Dujmovic D., Androic B., Lukasevic I., Composite Structures according to Eurocode 4, Worked Examples, 2014, Ernst & Sohn.

[6] Spacone E., Nonlinear Analysis of Steel-Concrete Composite Structures: State of the Art, A.M.ASCE, Journal of Structural Engineering, Vol. 130, No. 2, February 2004.

[7] Kuhlmann U., Rolle L., Gizejowski M., Kwasniewski L., Barcewicz W., Izzuddin B. A., Pereira M., Composite structures, Robustness of Structures, Proceedings of the Final Conference of COST Action TU601, COST, 05.2011.

[8] Cvetanovski P., Composite structures, printed lectures, 2011, Skopje, R. Macedonia.