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Nonlinear Finite Element Analysis of Optimally Designed Steel Angelina™ Beams

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***Abstract*—**Web-expanded steel beams provide an easy and economical solution for the systems having longer structural members. The main goal of manufacturing these beams is to increase the moment of inertia and section modulus, which results in greater strength and rigidity. Until recently, there were two common types of open web-expanded beams: with hexagonal openings, also called castellated beams, and beams with circular openings referred to as cellular beams, until the generation of sinusoidal web-expanded beams. In the present research, the optimum design of a new generation beams, namely sinusoidal web-expanded beams, will be carried out and the design results will be compared with castellated and cellular beam solutions. Thanks to a reduced fabrication process and substantial material savings, the web-expanded beam with sinusoidal holes (Angelina™ Beam) meets the economic requirements of steel design problems while ensuring optimum safety. The objective of this research is to carry out non-linear finite element analysis (FEA) of the web-expanded beam with sinusoidal holes. The FE method has been used to predict their entire response to increasing values of external loading until they lose their load carrying capacity. FE model of each specimen that is utilized in the experimental studies is carried out. These models are used to simulate the experimental work to verify of test results and to investigate the non-linear behavior of failure modes such as web-post buckling, shear buckling and vierendeel bending of beams.

***Keywords*—**Steel structures, web-expanded beams, Angelina™ beam, optimum design, failure modes, finite element analysis.

I. Introduction

THE idea of increasing inertia of steel beams by increasing the height of the beams reveals web opening steel beams. Yet, increasing the height of the web and occurring holes in the web causes increasing buckling on the web and slenderness of the steel beam. There are mainly three types of open web-expanded beams: with hexagonal openings also called castellated beams and beams with circular openings referred to as cellular beams and beams with sinusoidal openings described as Angelina™ steel beams [1]-[3]. Among these, Angelina™ beams are more attractive with their sinusoidal web holes with regard to architecture and engineering. Sinusoidal curves are designed for restraining concentration of stress.

The FE method is very appropriate for estimating the results of realistic characteristic and calculating stresses at isolated areas of expanded open-web steel beams [4]. Although FE method is useful, this method is time consuming in obtaining nonlinear solutions. Improving in the computer technology and advances in FE software have made this method more effective, recently.

In this study, previously tested optimally designed Angelina™ steel beams under various loading and having several sizes are simulated via FEA by using ANSYS Workbench v15 software. The modeled Angelina™ steel beams were optimized using one recent stochastic search technique called the hunting search algorithm [5]. Then obtained FEA results are compared with the experimental results with regard to total displacement and nonlinear behavior of failure modes such as web-post buckling, shear buckling and Vierendeel bending of beams [6].

II. Mesh Generations on Angelina™ Beams with ANSYS Program

In the process of FEA, meshing of geometry has great importance. Four types of meshing generations are available in ANSYS Workbench_v15 such as Sweep, Tetrahedrons, Hex-dominant and Automatic meshing generations. As Angelina™ beams cannot be swept; sweep meshing generation method is not investigated in the meshing step. Other meshing generation types for NPI_SB_200 compared each other with regard to number of nodes and number of elements for the same meshing size, which is 50 mm. The test specimen identification is pictured in Fig. 1.

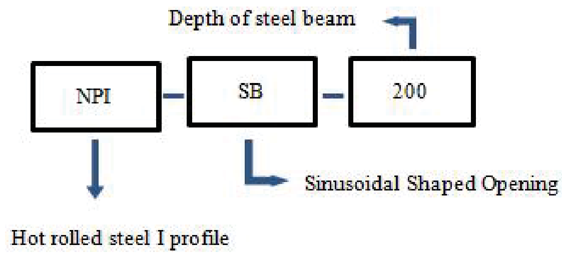

Fig. 1 Test specimen identification

It is shown that in Fig. 2, three different meshing generations applied to Angelina™ beam has various element number and node number in same mesh size. For the meshing generation hex-dominant, 43,941 nodes and 15,252 elements are occurred. When the mesh type is taken as automatically,

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the Angelina™ beam consist of 42,943 nodes and 19,843 elements. Among these, tetrahedron generation meshing renders 42,866 nodes and 20,271 elements. Hence tetrahedron meshing is found appropriate for the meshing generation of the beam (Fig. 3).

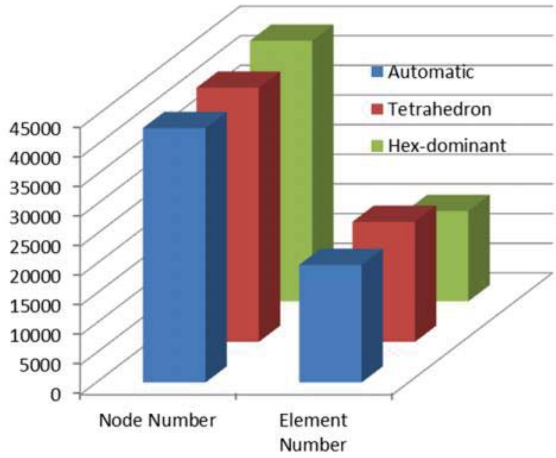

Fig. 2 Number of nodes and number of element for the NPI_SB_200 which has 50 mm meshing size

III. Nonlinear Solution of NPI_SB_200 Angelina™ Beam

Fig. 4 demonstrates static structure of FEA. 75047 N force, which supplied the experimental test results applied to the middle of NPI_SB_200 beam, while the end of the beam is supported using remote displacement. To entirely represent real experimental tests, force is applied to the area as in experimental test studies.

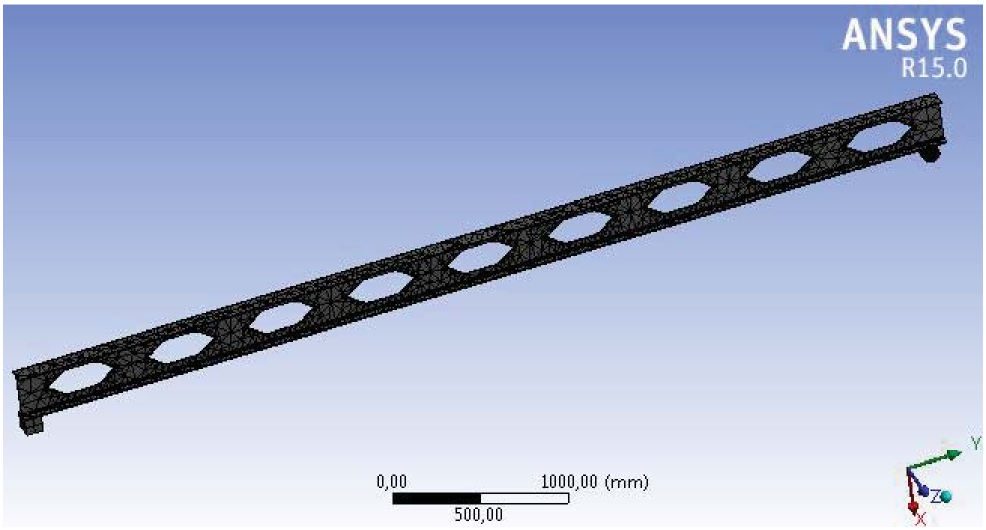

Fig. 3 Tetrahedron meshing generation on NPI_SB_200 in 50 mm mesh size

Nonlinear material is defined to be taken as a more precise solution. Material model of beams is selected as bilinear isotropic material model. Mechanical properties of material determined through tensile tests of coupons. Modulus of elasticity and yield stress, are respectively entered 200 GPa and 275 MPa. Tangent modulus is calculated as 390 MPa using material test data. Load is applied in 10 steps linearly growing from 0 N (Fig. 5).

The mind-span displacement value is obtained from the nonlinear analysis of NPI_SB_200 Angelina™ beam. When the load exceeds 75047 N, 124.79 mm mid-span displacement is read as shown in Fig. 6.

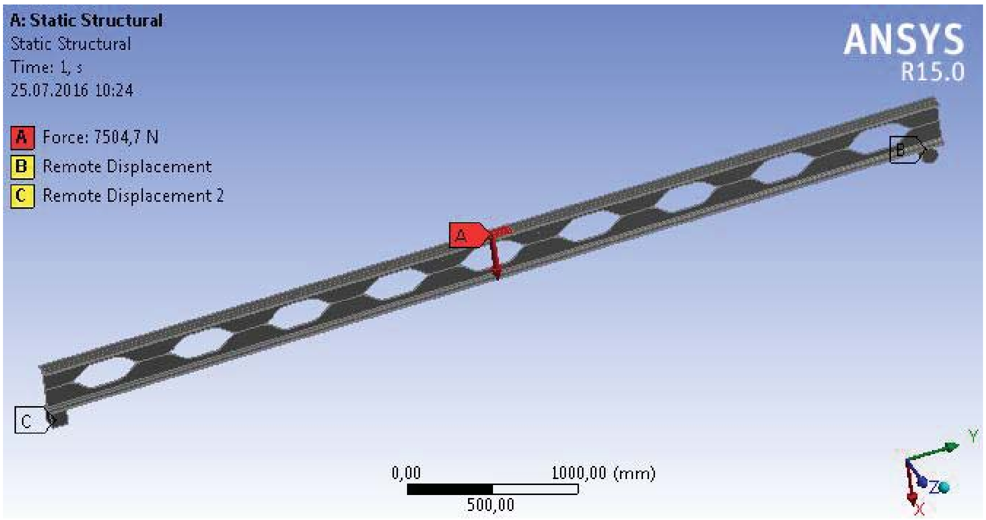

Fig. 4 Static structure of NPI_SB_200 Angelina™ beam

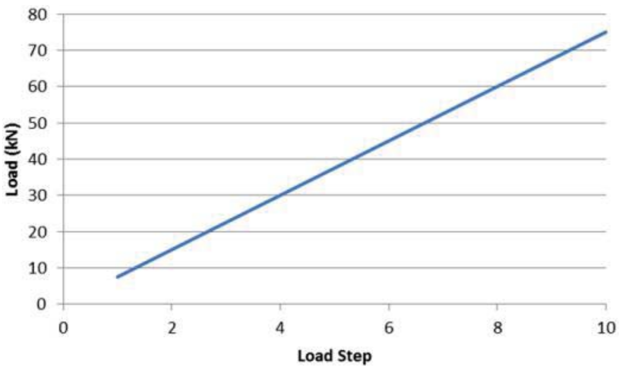

Fig. 5 Load steps are used in nonlinear FEA of NPI_SB_200 Angelina™ beam

The Von Mises stress value is obtained from the nonlinear analysis of NPI_SB_200 Angelina™ beam. When the load exceeds 75047N, 313.44 MPa equivalent stress is read, as shown in Fig. 7.

The shear stress value obtained from nonlinear analysis of NPI_SB_200 Angelina™ beam. When the load exceeds 75047N, 140.22 MPa stress is read, as shown in Fig. 8.

When nonlinear analysis results are compared with the test results, it is observed that the nonlinear analysis results correlate well with the experimental ones and the discrepancies are within 11.54% (Fig. 9).

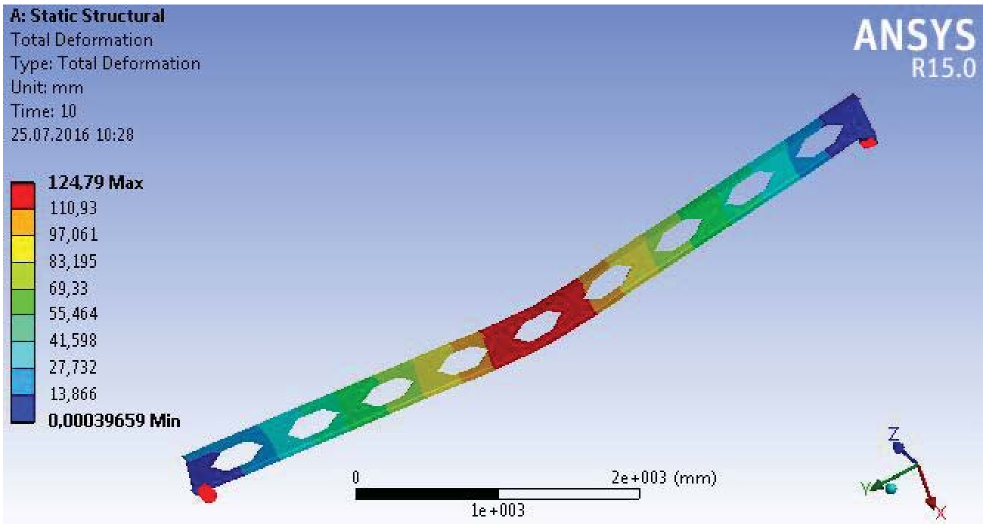

Fig. 6 Total deformation of NPI_SB_200 Angelina™ beam

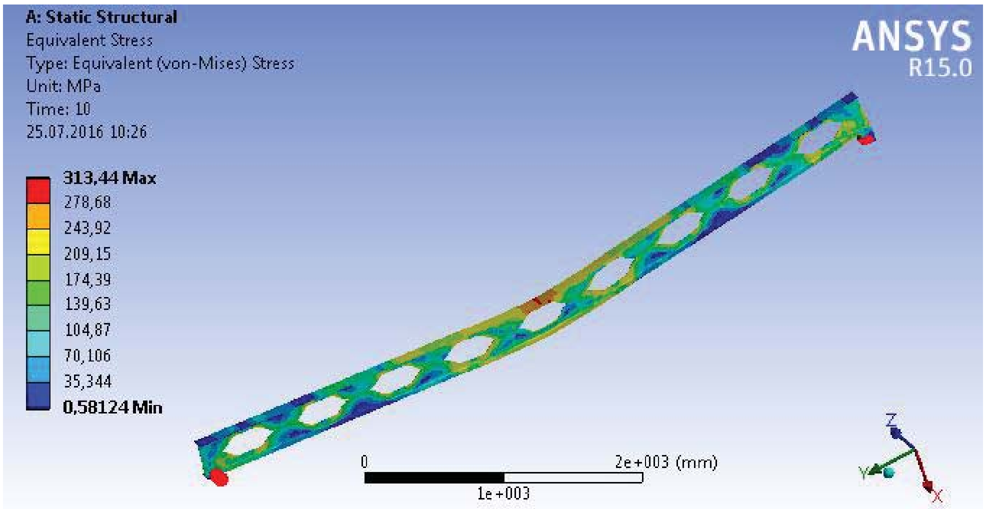

Fig. 7 Equivalent stress of NPI_SB_200 Angelina™ beam

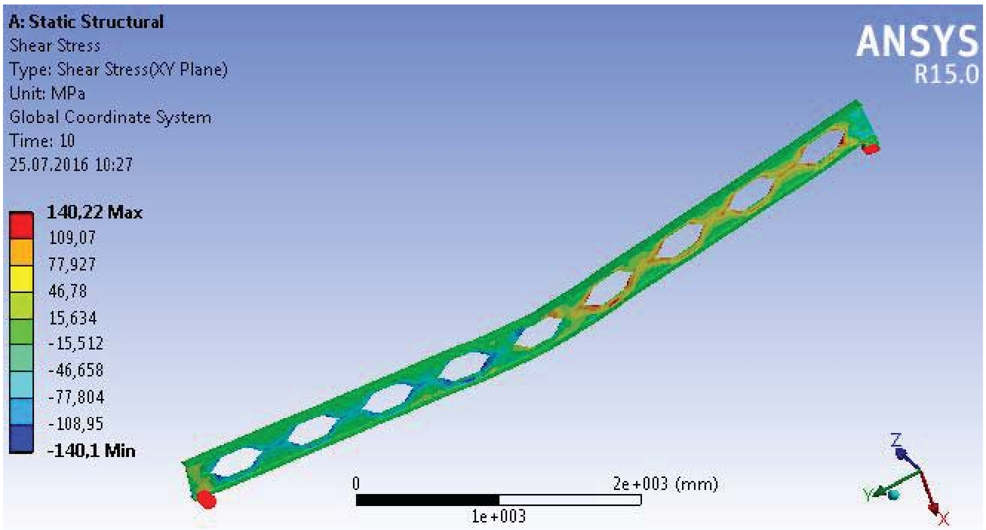

Fig. 8 Shear stress of NPI_SB_200 Angelina™ beam

IV. Nonlinear Solution of NPI_SB_240 Angelina™ Beam

Fig. 10 demonstrates the static structure of the FEA. The 130350N force, which supplied the experimental test results applied to the middle of the NPI_SB_240 beam and the end of beam is supported using remote displacement. To entirely represent real experimental tests, force applied to the area in the experimental test studies uniformly.

After the material is modeled as NPI_SB_200, load is applied in 10 steps linearly, growing from 0N to N. (Fig. 11)

The mind-span displacement value obtained from the nonlinear analysis of NPI_SB_200 Angelina™ beam. When the load exceeds 130350N, 88.40 mm mid-span displacement is read as shown in Fig. 12.

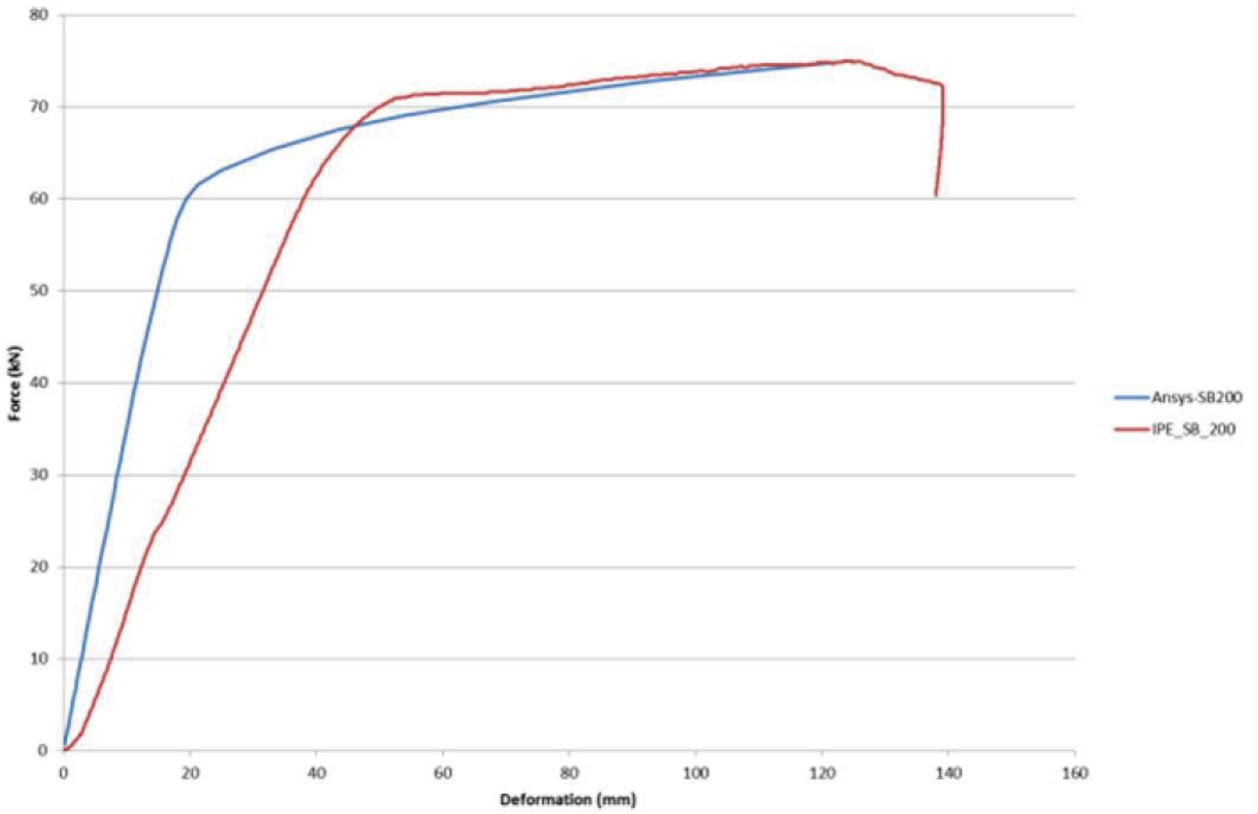

Fig. 9 Load-displacement curve of NPI_SB_200 Angelina™ beam

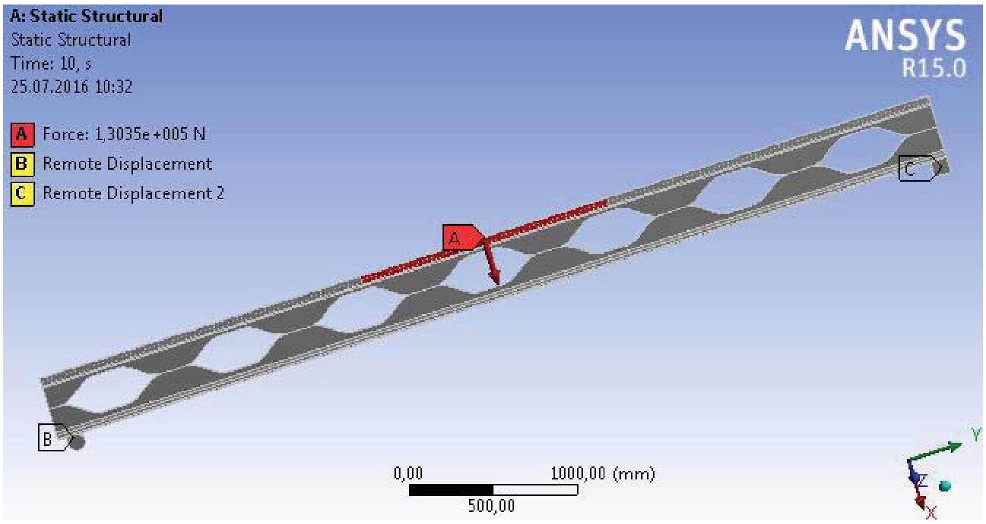

Fig. 10 Static structure of NPI_SB_240 Angelina™ beam

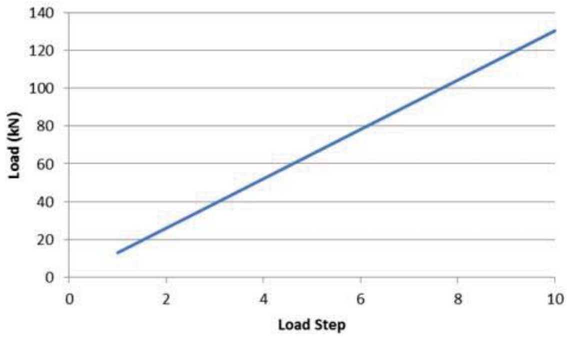

Fig. 11 Load steps are used in nonlinear FEA of NPI_SB_240 Angelina™ beam

The equivalent stress value obtained from nonlinear analysis of NPI_SB_240 Angelina™ beam. When the load exceeds 130.350N, 398.97 MPa Von Mises stress is read, as shown in Fig. 13.

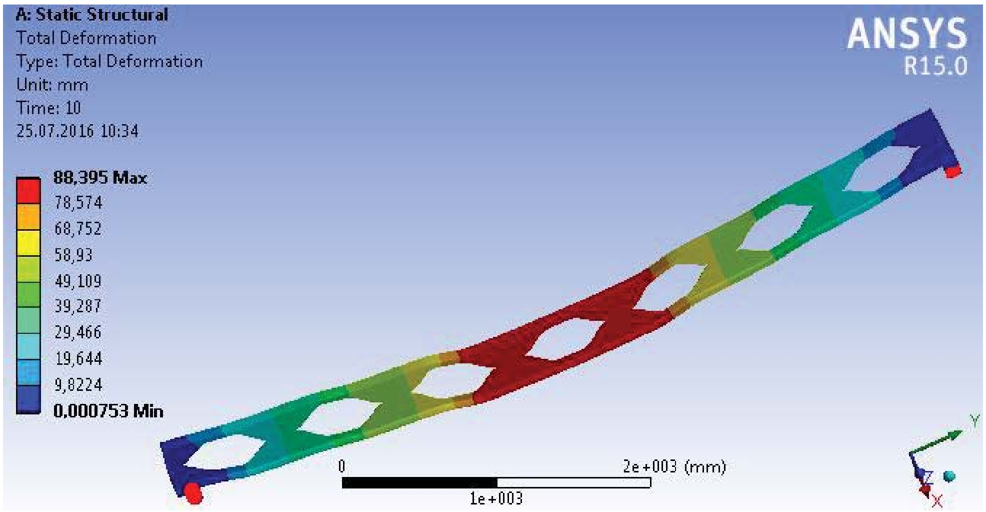

Fig. 12 Total deformation of NPI_SB_240 Angelina™ beam

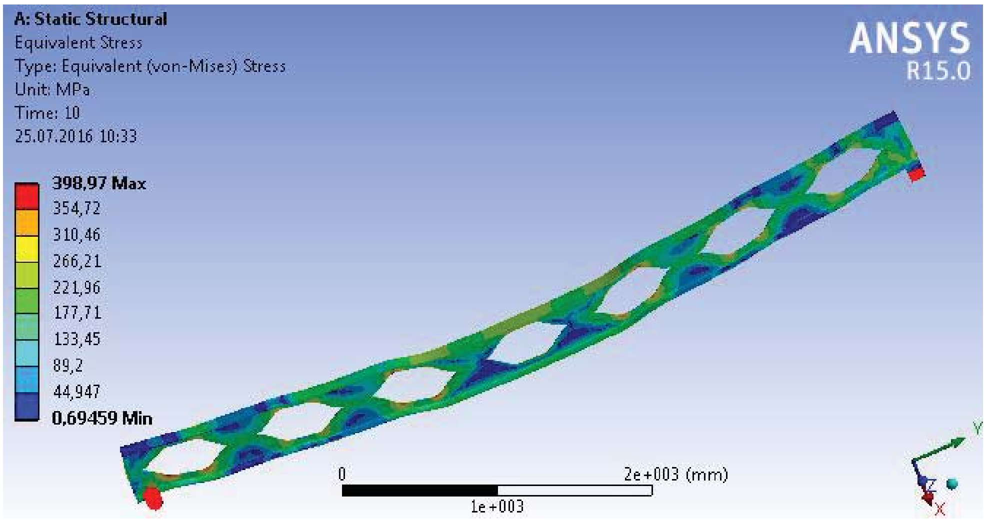

Fig. 13 Equivalent stress of NPI_SB_240 Angelina™ beam

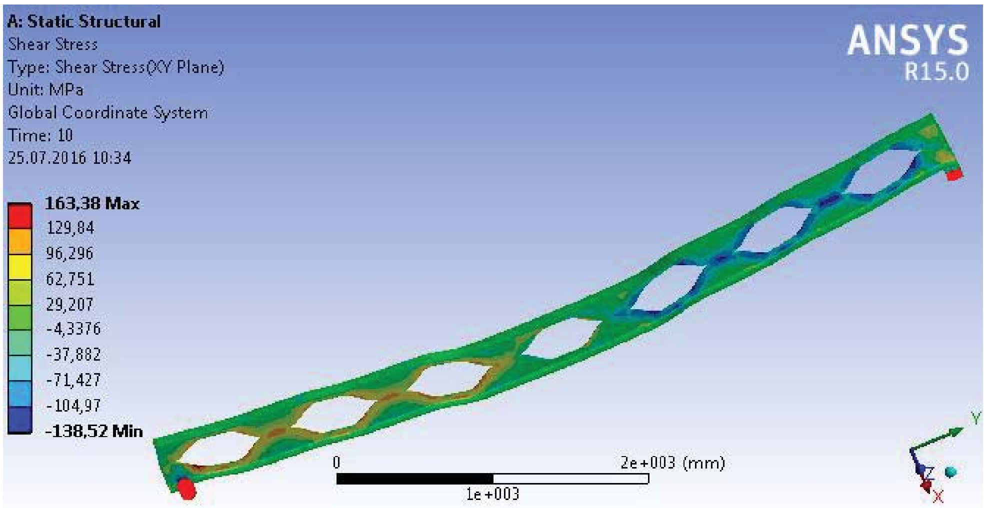

Fig. 14 Shear stress of NPI_SB_240 Angelina™ beam

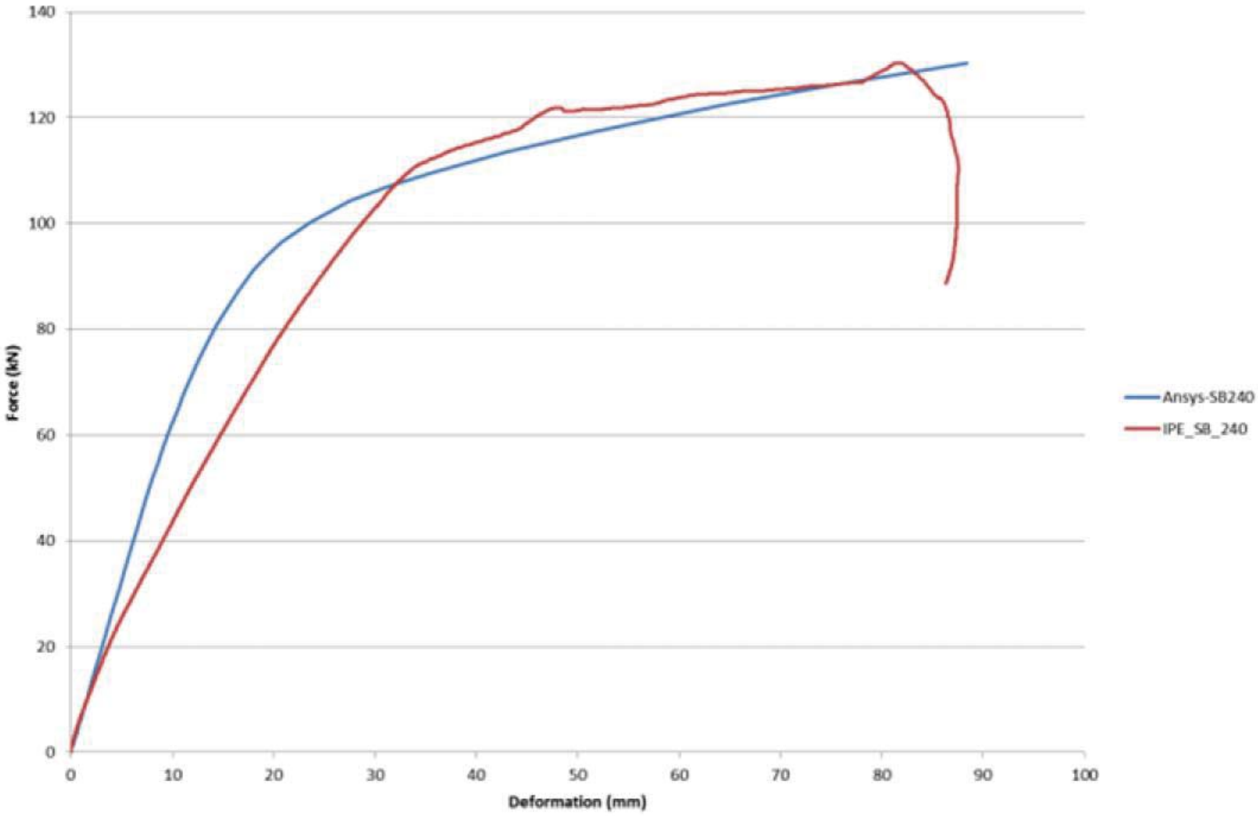

Fig. 15 Load-displacement curve of NPI_SB_240 Angelina™ beam

The shear stress value obtained from the nonlinear analysis of the NPI_SB_240 Angelina™ beam. When the load exceeds 130.350 N, 163.38 MPa shear stress is read, as shown in Fig. 14.

When nonlinear analysis results comparing with test results, it is observed that the nonlinear analysis results correlate well with the experimental ones and the discrepancies of 0.97% are within the suitable range (Fig. 15).

Load is applied in 10 steps linearly growing from 0 N to 252481 N (Fig. 17).

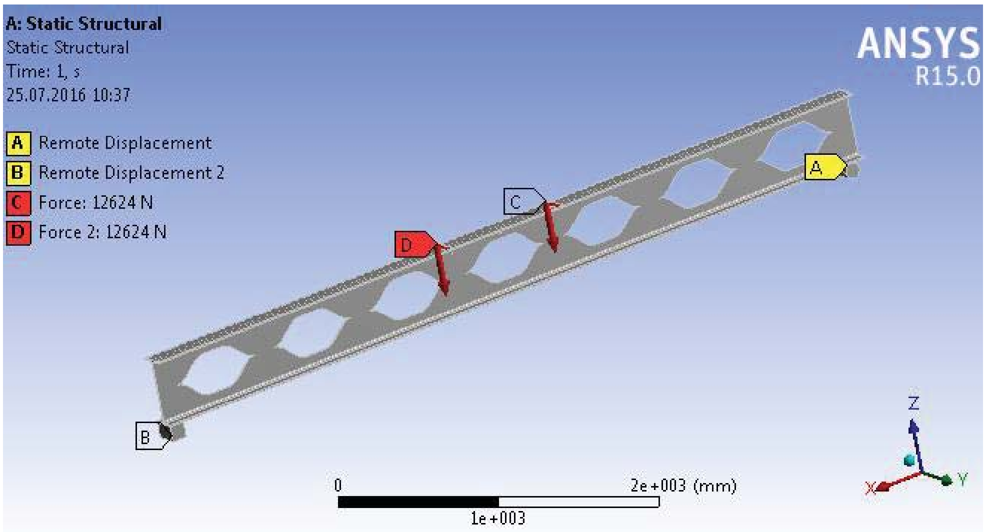

Fig. 16 Static structure of NPI_SB_300 Angelina™ beam

The mind-span displacement value obtained from the nonlinear analysis of the NPI_SB_300 Angelina™ beam. When the load exceeds 252481 N, 46.65 mm mid-span displacement is read, as shown in Fig. 18.

The Von Mises stress values are obtained from the nonlinear analysis of the NPI_SB_300 Angelina™ beam. When the load exceeds 252481N, 575.39 MPa maximum equivalent stress is read, as shown in Fig. 19.

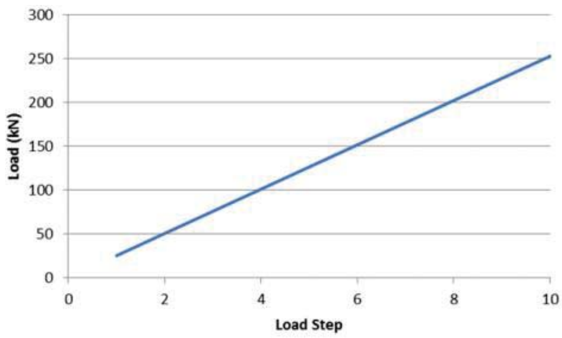

Fig. 17 Load steps are used in nonlinear FEA of NPI_SB_300 Angelina™ beam

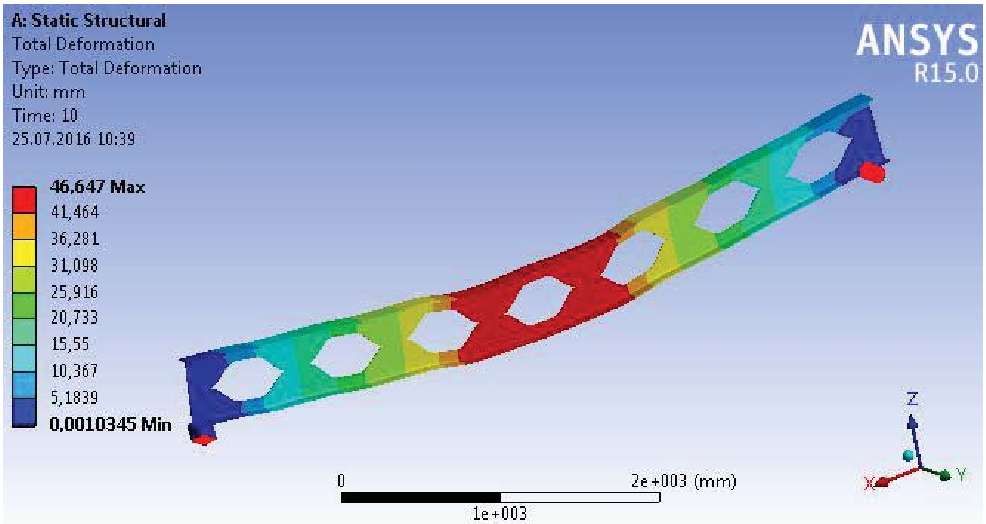

Fig. 18 Total deformation of NPI_SB_300 Angelina™ beam

The shear stress value obtained from nonlinear analysis of NPI_SB_300 Angelina™ beam. When the load exceeds 252481 N, 67.67 MPa maximum shear stress is read as shown in Fig. 20.

When nonlinear analysis results comparing with test results, it is observed that the nonlinear analysis results correlate well with experimental ones and the discrepancies are within 6.4% (Fig. 21).

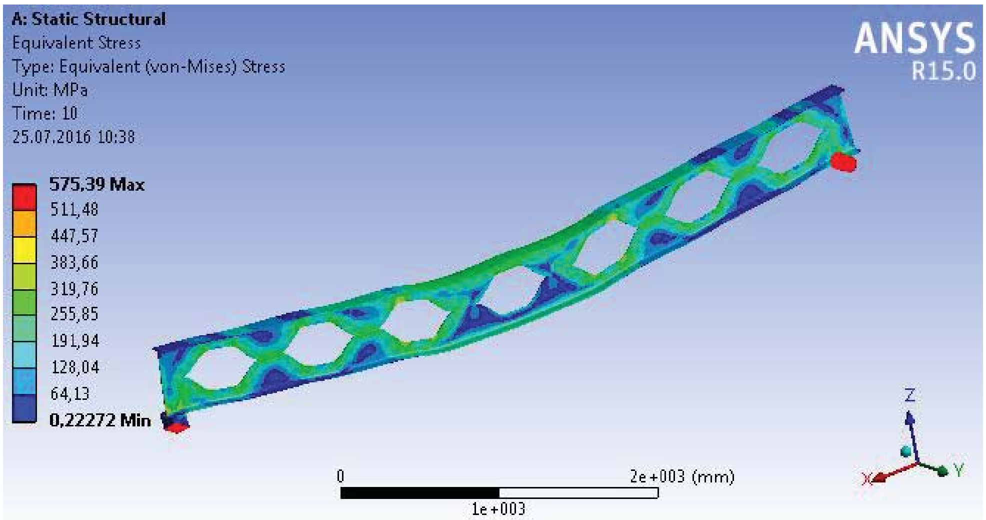

Fig. 19 Equivalent stress of NPI_SB_300 Angelina™ beam

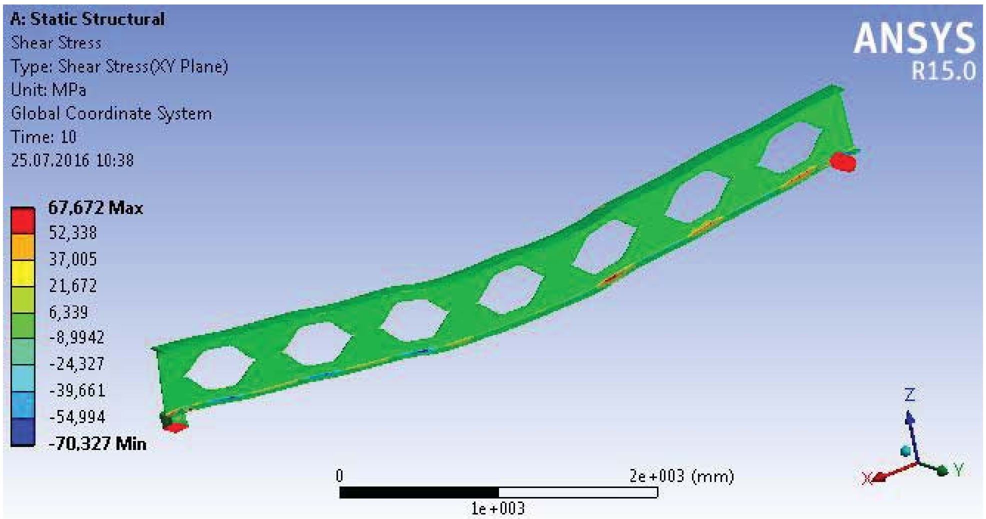

Fig. 20 Shear stress of NPI_SB_300 Angelina™ beam

V. Conclusion

In the present research, the experimental tests of steel Angelina™ beams is simulated by using ANSYS-Workbench finite element software program to verify the test results, and to a good degree, with the non-linear behavior of failure modes. Load-deflection diagrams results demonstrate that the nonlinear analysis results correlate well with experimental ones and the discrepancies are within the suitable range. Comparison of FEA and test results for NPI_SB_200, NPI_SB_240, and NPI_SB_300 present, respectively, 11.54%, 0.97% and 6.4% accurate displacement ratios. Besides it is shown that increasing height of beam causes decreasing of the displacement capacity of sinusoidal web opening beams.

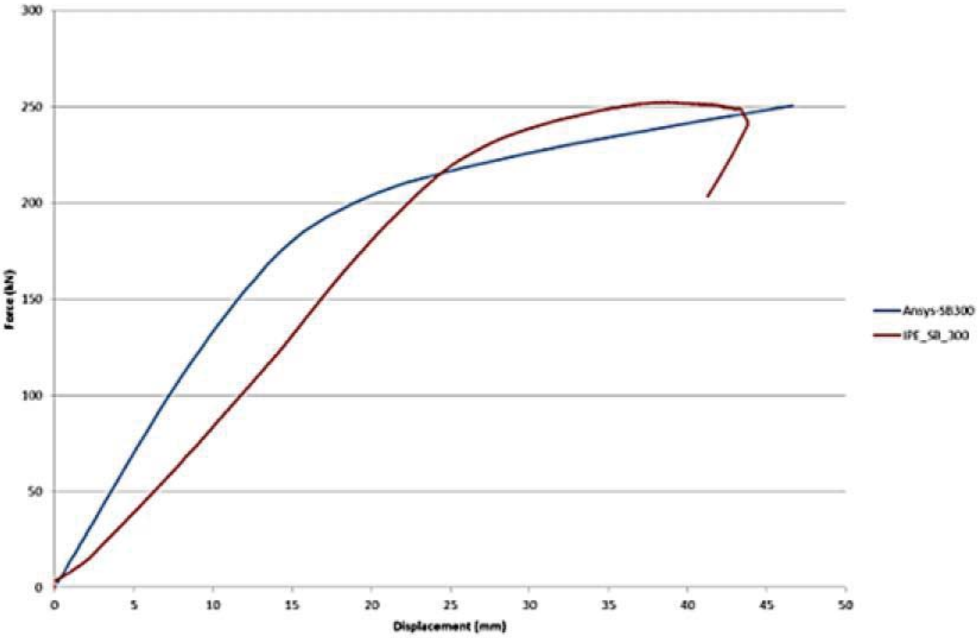

Fig. 21 Load-displacement curve of NPI_SB_300 Angelina™ beam

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