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Nonlinear finite element analysis of optimally designed steel cellular beams

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Abstract

Cellular beams became increasingly popular as an efficient structural form in steel construction since their introduction. Their sophisticated design and profiling process provides greater flexibility in beam proportioning for strength, depth, size and location of circular holes. The purpose of manufacturing these beams is to increase the overall beam depth, the moment of inertia and section modulus, which results in greater strength and rigidity. The objective of this study is to carry out non-linear finite element (FE) analysis of the cellular beams that were considered in the experimental study in order to determine their ultimate load carrying capacity for comparison. The finite element 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. FE models of steel cellular beams 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.

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1. Introduction

Steel I-beam sections can be modified to intensify their strength by creating an open-web section from an original beam. This is achieved by cutting the web of the root beam in a certain pattern and then re-welding the two halves to each other. As a result of these processes the overall beam depth increases which in return causes increase in the capacity of the section. There are two common types of open web beams: beams with hexagonal openings, also called as castellated beams [1-3] and beams with circular openings referred to as cellular beams [4-6]. Since the 1950's the high strength to weight ratio of castellated beams has been a desirable item to structural engineers in their efforts to design even lighter and more cost efficient steel structures.

The emergence of cellular beams was firstly for architectural application, where exposed steelwork with circular web openings in the beam was considered aesthetically pleasing. Cellular beams are steel sections with circular openings that are made by cutting a rolled beams web in a half circular pattern along its centerline and re-welding the two halves of hot rolled steel sections. This circular opening up of the original rolled beam increases the overall beam depth, moment of inertia and section modulus, while reducing the overall weight of the beam.

Firstly, finite element models of steel cellular beams are used to simulate the experimental work in order to verify of test results and to investigate the non-linear

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behavior of failure modes such as web-post buckling, shear buckling and vierendeel bending of steel cellular beams [7-9]. Then, the design techniques developed are used to find the optimum solutions of different cellular beams where the design constraints are implemented as per the BS5950 provisions [10]. ANSYS-workbench finite element modeling program is used to develop a three dimensional finite element beam model in this study. Nonlinear finite element models of NPI profile based steel cellular beam specimens are built to determine maximum values and locations of stress, strain and displacement concentrations under point loading. The non-linear analyses results of NPI profile steel cellular beams have been compared with results obtained from experimental studies [11]. Before starting the process of analysis, geometric dimensions of cellular beams are drawn with SOLIDWORKS program. After applying inputs related with prepared models of steel cellular beams, analysis process is initiated by using the software ANSYS. Material properties of the steel cellular beams are extracted from the material library; which covers standard concrete and steel has the ability to create user defined custom materials for non-standard applications. A nonlinear elastic material model is used for NPI_240 and NPI_260 steel NPI sections with Young's modulus of 1.9×10^5 and 1.95×10^5 MPa with average values found from tension tests [11] and Poisson's ratio taken as 0.3 and the density of steel taken as 7.85×10^{-6} kg/mm. Tensile yield stress values obtained are respectively 390 and 285 MPa for NPI_240 and NPI_260 steel profiles according to tensile testing results. In the same way, tensile ultimate stress values obtained are respectively 495 and 400 MPa for NPI_240 and NPI_260 steel beam profiles. During FEA process, the structure is divided into small and simple elements to calculate individual deformation easily. Tetrahedron volume finite elements are selected in the modeling of cellular beams. In this study, 10-node high-order element has been selected as this element has a quadratic displacement behavior and is well suited to model irregular meshes compared to other types.

2. Mesh Generations on Cellular Beams with ANSYS Program

There are four types of meshing generations in ANSYS program. These methods are called Sweep, Automatically Generated, Tetrahedrons and Hex-Dominant. Since non-sweepable bodies force sweep method controlling, cellular beams cannot be swept. Other meshing generation types, hex-dominant, automatically generated and tetrahedrons are tested for finite element model of cellular beams to compare their created nodes and elements for the same mesh sizing. In this purpose, NPI_240 cellular beam is used to mesh with these generation types. Mesh size is taken as 100 mm for each method.

Table 1 Number of nodes and elements for mesh types

Mesh type	Number of nodes	Number of elements
Hex – Dominant	6968	1877
Automatically Generated	8847	3724
Tetrahedrons	9413	4019

It is observed from Table 1 that when automatically generated, tetrahedrons and hex-dominant meshing methods give different values for nodes and elements. When the mesh type is taken as hex-dominant for 100 m mesh size, the beam consists of 1877 elements and 6968 nodes. For the same mesh size, automatically-generated consists of 3724 elements and 8847 nodes. In comparison with other mesh types, tetrahedron meshing provides better size distribution for the beam across the model with 4019 elements and 9413 nodes. Therefore, tetrahedron meshing is selected for solving the cellular beam model.

Mesh sizing is important for accurate stress and displacement values. For this purpose, the tetrahedron mesh divides various sized mesh starting with 400 mm. When the stress and displacement values are stable, this mesh sizing can be applicable for FEM analysis. Fig. 1 illustrates that mesh sizing is important to find exact stress values. Fig. 1 also demonstrates that maximum stress values (respectively 501.27 MPa and 500.67 MPa) on the steel cellular beam are nearly the same as the taken mesh sizes of 50 mm and 25 mm. It means 25 mm mesh size can be used for FEM analysis of these beams.

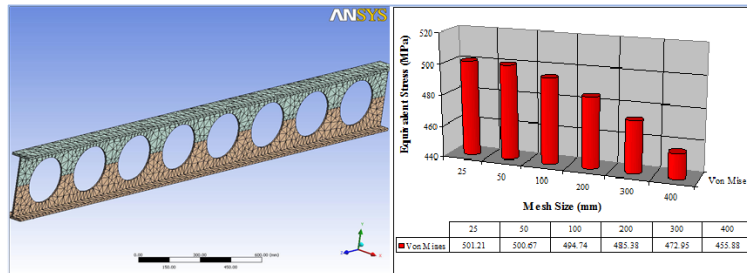


Fig. 1 Tetrahedron mesh generation and different mesh sizes and stress values

3. Nonlinear Solution of NPI_240 Cellular Beam

The details of analysis settings for NPI_240 beam in ANSYS Workbench are demonstrated in Fig. 2. 280 kN force, the average value obtained from experimental tests of steel cellular beams, is applied to the middle of the beam as 528 MPa pressure. When the load is applied to a particular point, the force stays inside meshes and sinks; however, ANSYS-workbench program does not analyze the cellular beam model. For this reason, the load is applied to the cellular beam as pressure as shown in the figure below. A bilinear isotropic material model (elastic modulus, $E = 1.9 \times 10^5$ MPa, tangent modulus, $ET = 390$ MPa) with Von-Mises yield criterion (yield strength, $F_y = 390$ MPa) was used for the steel of the cellular beam model the nonlinear material behavior of the beam. The material properties used to in the all NPI section beam models were determined through tensile tests of coupons taken from the test beams. Since the main objective of FEA was to determine beam failure behavior in web post regions, significant attention was paid on properly modeling the connection of the beam to the loading frame.

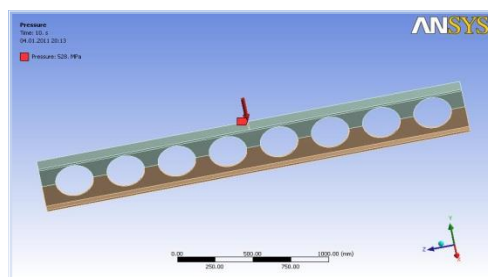


Fig. 2 Applying pressure to NPI_240 cellular beam

Different from the linear solution, the material effects of cellular beam in the program are defined as nonlinear in the analysis of cellular beams. The mid-span displacement values obtained in the non-linear analysis of NPI-240 cellular beam is tabulated in Table 2 for the load increment of 28kN starting from 28kN. It is apparent from the table that when the load reaches 280 kN, which is the average value obtained from experiments, the nonlinear displacement value is 42.58% more than the linear displacement value. It is clear that after the load is increased, the axial forces increase in the beam and their effect on the flexural bending of the beam become more emphasized.

Table 2 Displacement values for nonlinear analysis at middle part of NPI-240 cellular beam

Number of steps	Applied load (kN)	Displacement (mm)
1	28	0.8295
2	56	1.6619
3	84	2.5021
4	112	3.3511
5	140	4.2524
6	168	5.2212
7	196	6.2619
8	224	7.4551
9	252	9.2487
10	280	13.2791

When the ultimate load, 280 kN, is applied to the middle part of the beam as pressure, maximum equivalent stress which is 501.21 MPa, shown in Fig. 3, occurs around the holes. Fig. 3 also shows the maximum displacement that occurred in the middle of the beam. It was measured as 15.458 mm at upper flange and 14.071 mm at lower flange.

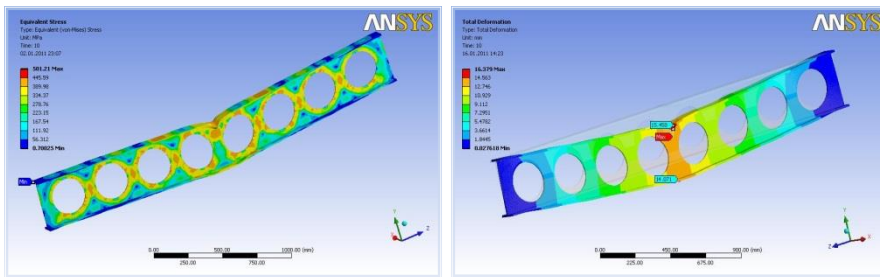


Fig. 3 Equivalent Stress and Deformation Values on NPI_240 Cellular Beam

When the same ultimate value, 280 kN, is applied to the middle part of the NPI-240 cellular beam, maximum normal stress which is 431.66 MPa occurred at web-post and maximum shear stress which is 352.0 MPa, shown in Fig. 4, occurred around the area of support.

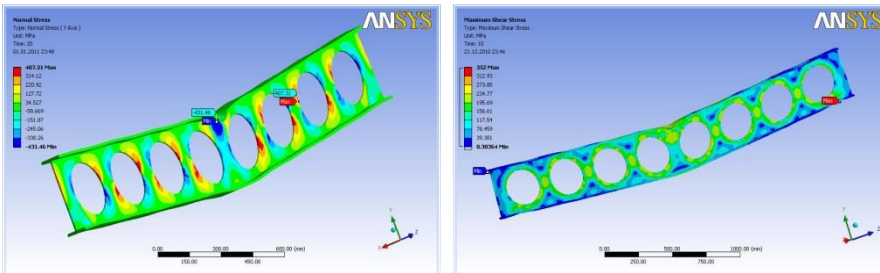


Fig. 4 Normal and shear stress values on NPI_240 cellular beam

When the experimental results obtained are compared with those of the nonlinear finite analysis values, the deflection values obtained from NPI_240_TEST_4 are 8.48% lower than the nonlinear displacement value for upper flange and 6.22% lower than the

nonlinear displacement one for lower flange. The load-deflection diagram, comparing finite element model with the curve of corresponding experimental NPI_240_TEST_4 cellular beam specimen are illustrated in Fig. 5 and Fig. 6, respectively.

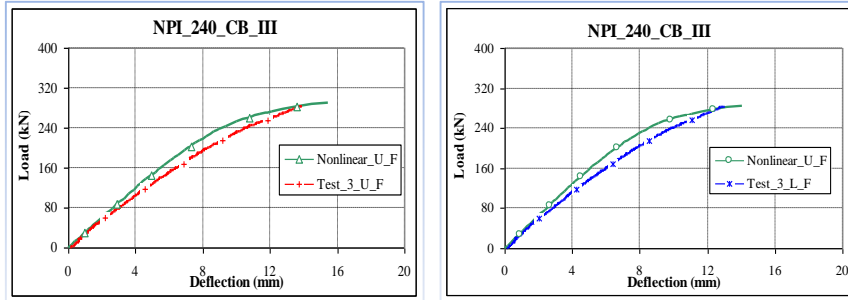


Fig. 5 Load-deflection-curve for upper and lower flange of NPI_240_TEST3

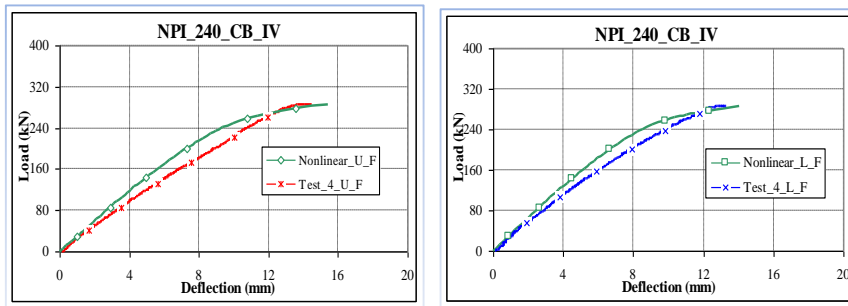


Fig. 6 Load-deflection-curve for upper and flange of NPI_240_TEST4

4. Nonlinear Solution of NPI_260 Cellular Beam

The details of analysis settings for NPI_260 steel cellular beam in ANSYS workbench program are shown in Fig. 7.. 220 kN force, the average value obtained from experimental tests of these steel cellular beams, is applied at the middle of the upper flange as 425 MPa pressure in 10 steps. When 220 kN load was applied to the middle of the beam as shown above, maximum equivalent stress occurred at the middle part of upper flange. It was also determined as 494.42 MPa after the application of load in 10 steps as illustrated in Figure 7. Fig. 8 shows the maximum displacement occurred in the middle of the beam as expected with an 18.969 mm for upper flange and 12.612 mm for lower flange.

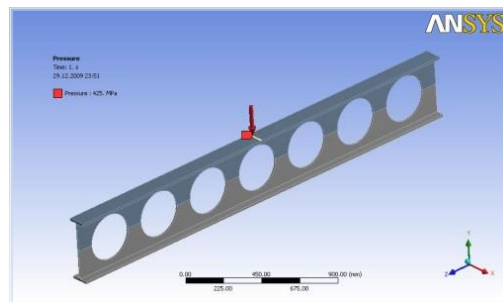


Fig. 7 Applying pressure to NPI_260 cellular beam

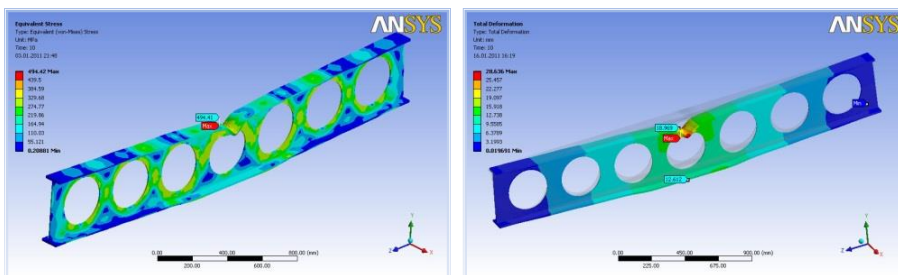


Fig. 8 Equivalent stress and deformation values on NPI_260 cellular beam

When the same ultimate load, 220 kN, is applied to the middle part of the NPI-260 cellular beam, maximum normal stress which is 303.40 MPa, shown in Fig. 9, occurred at web-post and maximum shear stress which is 269.06 MPa, also shown in Fig. 9, occurred around the area of support respectively.

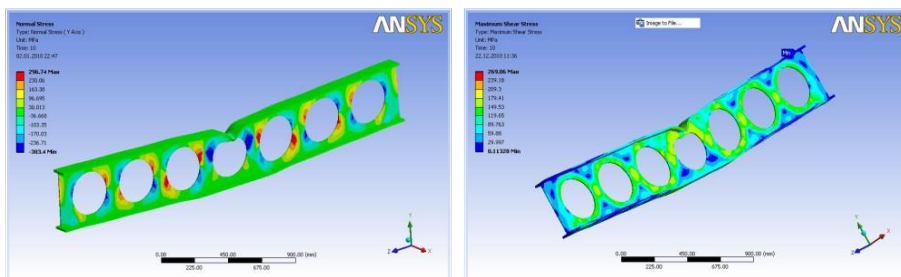


Fig. 9 Normal and shear stress values on NPI_260 cellular beam

When the experimental results are compared with those of nonlinear solution values, it is found that the deflection values obtained in NPI_260_TEST_1 are 9.56% more than the nonlinear displacement value for upper flange and 11.06% more than the nonlinear displacement one for lower flange. Load-deflection diagrams that are obtained by the finite element model and the experimentally for NPI_260_TEST_1 cellular beam specimen are illustrated in Fig. 10.

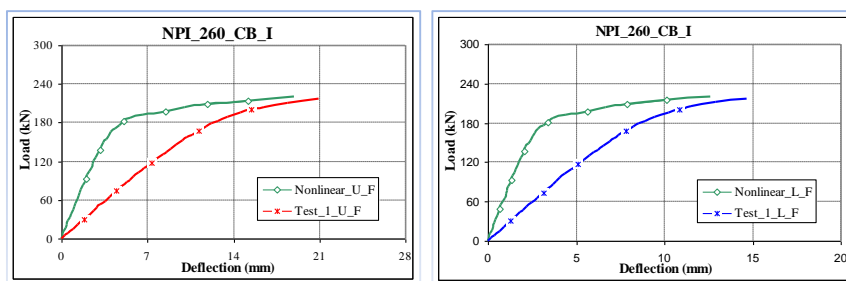


Fig. 10 Load-deflection-curve for upper and lower flange of NPI_260_TEST1

When the obtained experimental results are compared with those of nonlinear solution values, the deflection values obtained NPI_260_TEST_2 are 9.08% more than the nonlinear displacement value for upper flange and 8.91% more than the nonlinear displacement one for lower flange. Load-deflection diagrams that are obtained by the finite element model and experimentally for NPI_260_TEST_2 cellular beam specimen are illustrated in Fig. 11.

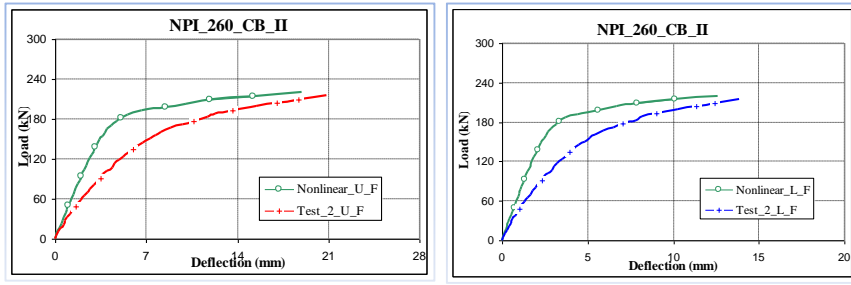


Fig. 11 Load-deflection-curve for upper and flange of NPI_260_TEST2

When the experimental results are compared with those of nonlinear solution values, it is noticed that the deflection values obtained experimentally in NPI_260_TEST_3 are 7.44% more than the nonlinear displacement value for upper flange and 7.69% more than the nonlinear displacement one for lower flange. Load-deflection diagrams that are obtained by the finite element model and experimentally for NPI_260_TEST_3 cellular beam specimen are illustrated in Fig. 12.

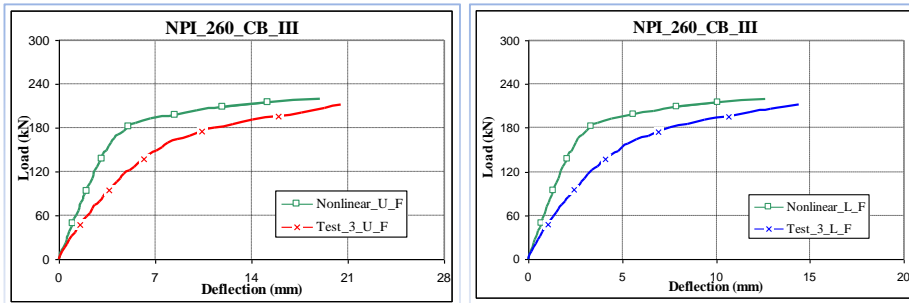


Fig. 12 Load-deflection-curve for upper and flange of NPI_260_TEST3

When the experimental results are compared with those of nonlinear solution values, it is found that the deflection values obtained experimentally in NPI_260_TEST_4 are 10.68% more than the nonlinear displacement value for upper flange and 12.59% more than the nonlinear displacement one for lower flange. Load-deflection diagrams that are obtained by the finite element model and the experimentally for NPI_260_TEST_4 cellular beam specimen are illustrated in Fig. 13.

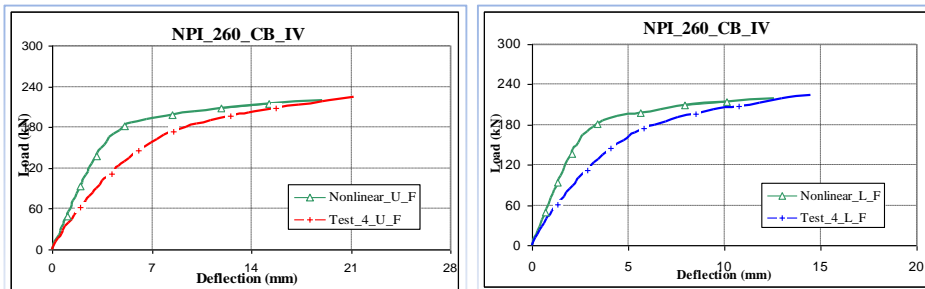


Fig. 13 Load-deflection-curve for upper and flange of NPI_260_TEST4

5. Conclusion

In this study, the experimental work is simulated by using ANSYS-workbench FE integrated software program to verify the test results and to a good degree with the non-

linear behavior of failure modes such as web-post buckling and vierendeel bending of NPI_240 and NPI_260 section steel cellular beams. Failure loads obtained from experimental tests are compared with FE analysis values for three cellular beams. Load-deflection diagrams shown in the study reveal that average deflection values obtained from experimental tests for upper and lower flange of NPI_240 section beams under 280 kN load are respectively 9.31% and %7.01 lower than FE analysis results which is the closest value obtained between them. Moreover, the failure loads obtained from experimental tests are compared with FE analysis values for NPI_260 cellular beam. The load-deflection diagrams shown in the study also reveal that average deflection values obtained from experimental tests for upper and lower flange of NPI_260 cellular beams under 220 kN load are respectively 9.19% and 10.06% more than from FEA results which is again within the reasonable range. These results demonstrate that the nonlinear analysis results correlate well with experimental ones and the discrepancy is within 10%.

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