Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 4, No. 7, July, 2018

Finite Element Analysis and Optimization of Steel Girders with External Prestressing

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Received 16 May 2018; Accepted 01 July 2018

Abstract

Optimization is a process through which the best possible values of design variables are achieved under the given of constraints and in accordance to a selected optimization objective function. Steel I-girders have been used widely in different fields, which are generally fabricated by connecting two plate flanges, a flat web and a series of longitudinal or transverse stiffeners together. The use of steel girder with external prestressing has been used in many countries as a means of strengthening bridges. The purpose of this paper is to develop a finite element model for the optimization of a steel girder with external prestressing. The ANSYS finite element software package was used to find the optimum cross section dimension for the steel girder. Two objective functions are considered in this study there are optimization of the strain energy and total volume of the girder. The design variables are the width of top flange, the thickness of top flange, the width of bottom flange, the thickness of bottom flange, the height of the web, the width of the web and area of prestressing tendons. Two type of steel girder are considered there are steel girder without prestressing and steel girder with prestressing. The results for volume minimization shows that the optimum cross section for steel girder with prestressing smaller than for steel girder without prestressing.

Keywords: ANSYS; Finite Element; Optimization; Steel Girder; External Prestressing; Stiffener.

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1. Introduction

The use of External Prestressing (EP) has been used in many countries since the 1950s as a means of strengthening bridges or rehabilitatingiexisting bridges. It has been used to provide an economical and efficient solution for a wide range of bridges. The technique is growingiin popularity because of the minimalitrouble to traffic flow and the fast of installation. The principle prestressing is theiapplication of an axial load together with a hogging bending moment to increase the flexural capacity of a steel girder. It can also have a beneificial effect on shearicapacity [1].

EP is a prestress presented by wires placed outside of a structural member, the wires linked to the structural member through end-anchorages, deviators and profiled along the span at strategically located low and high points.

Steel Girder (SG) prestressed with high strengthiexternal wires have validated numerous advantages as compared with normal SGs. This benefit are extend the range of elastic performance previously yielding for the SG and increase in ultimate capacity of moment of SG. The stresses can then oppose the moment generated by theiloading. The amount of steel utilized in building, depended on yield strength alone, can.be decresed.by the use of wires with high-strength, thus decreasing the total cost of construction.

EP of girder oricomposite beams is generally used in bridge engineering and frequently to strengthenlexisting structures [2]. This practice can be applied to one span or continuous SG and reinforced concrete deck bridges. It is

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http://dx.doi.org/10.28991/cej-0309189

acknowledged that in prestressed girder and composite beamsiincremental stress happens.in the wires bending under the externaliloads. The stress fields in the girder and in the tendon based on the displacements of the wholeistructure [3].

Optimization techniquessmay be effective in finding alternative geometries of SG to improveetheir mechanical behaviour, particularly avoiding or reducing the bendingimoments.

Steel I-girders, which areigenerally fabricated byiwelding two plate flanges, a flat webiand a series of transverse or longitudinalistiffeners together, have been usediwidely in various fields, such as structurallengineering, architectural engineering and bridge engineering. Since 1960s, a large amount of experimental and theoretical studies on the behavior of plate girdersisubjected to shear or patch loading have been reported in the literature, and the behavior of the conventional I-girders are known well at present.

Many numericaliinvestigations were reported in the literatureehighlighting the structural performance of different types of steel bridges subjected to differenttloadings and different boundary conditions [4-9].The numerical investigationsiproposed Finite Element (FE) models, for the SG and the compositeegirder, which were developed to provide accurate analyses and betteriunderstanding for the behavior and stability of differentigirders [10]. Experimental work regarding the interaction of bending moment and shear force (M–V interaction) for longitudinally stiffened girders was conducted by Sinur [11].

Antoniou et al [12] developed a new kind of girder, appropriate for longispans .The load resisting mechanism of the system is deepened on the suitable shape of the girder which is determiined through a form-findiing procedure. This optimal geometry isichosen in such a way so that no bending moments appear under external loading. Additional prestressed cables, integrated into the girder, areiutilized as a means to limit vertiical displacements, thus acting as a passive displaceement control mechanism.

El-Khoury et al. [13] presented FE models using ABAQUS software program focused on single plate girder samples loaded and restrained in a fashion that mimickedigirders in high flexure and shear areas in horizontallyicurved bridges.

Park et al. [14] studied the slenderness boundaries for webs and flanges to rationallyievaluate the flange local buckling strength of longitudinallyistiffened I-girders. From this work, it is acknowledged that the bending resistance of a plateegirder significantly increases when the web is longitudinally stiffened. They found this additionalistrength can be attributedito the point that the stiffened web provides improved restraint to the rotation of the compression flanges as well as web bend-buckling strength.

Rana et al. [15] presented cost optimization method of a post-tensioned I-girder bridge. A global optimization algorithmnnamed EVOP (Evolutionary Operation) was used. The comparison was done between optimum design and a real life project named Teesta Bridge. This comparison leads up to 35% saving.

An optimization approach was presented by Ahsan et al. [16] to the design of PT, pre-stressed, simply supported, concrete I-girder bridges.

Hinton and Rao [17] studied the optimal structural design of folded prismatic shell and plate structures using the finite strip technique with Strain Energy (SE) minimization as an objective and allowed the cross sectional thickness and shape to be changed.

Sawant et all [18] studied a cost optimization procces of a post-tensioned I-girder is presented. The objective was to optimization the cost of the bridge systemnconsidering the cost of materiials. For a particular girder span andibridge width, the designivariables considered for the cost minimization of the bridge system are girder depth, bottom flange, top flange width, thickness and number of cables. Designiconstraints for the optimization were considered accordingito AASHTO.

Park et al. [19] presented a seriesiof numerical analyses and they found that the American Association of State Highway and TransportationnOfficials' (AASHTO's) load and resistance factoridesign (LRFD) requirements provide highly conseervative estimates of the FLB strength of longiitudinally stiffened plate girders, especially in noncompact sections.

In this paper, 3-dimensional FE model was introduced using ANSYS software to study the optimum design of steel I-girder with EP. Experimental steel I-girder from literature [11] was chosen for numerical analyses verification, and good agreement was achieved between test and numerical results. The optimum size of girder was calculated. Optimization routines for ANSYS use three kinds of variables that describe the design optimizationiprocess: the objective function, design variables and constraints. ANSYS Parametric Design Language (APDL) represents the objective function these variables by scalar the objective function parameters. The use of APDL is a important step in the optimization procedure.

2. Finite Element Modeling

To represent the SG in FE, 4-node shell element needed. For this purpose, a Shell181 element was used to model the SG. This element has four nodes with six degrees of freedom at each node: rotations about the x, y, and z-axes and translations in the x, y, and z directions. The element is used for linear and nonlinear applications. The element has also stress stiffening, plasticity and large deflections [20].

The model used for tendons modeling must have the ability to existing plasticity, swelling, stress, stiffness, creep, and large deflection to show the behavior of prestressing tendons. LINK8 is a discrete model and spare element, which is used for many engineering applications, LINK8 can model the trusses, sagging cables, links and springs. This element is a 3-D uniaxial and spare compression-tension element. LINK8 has 3-degrees of freedoms at each node, translations in the x, y and z-directions [20].

Material properties shows a significant role in ANAYS analysis. Accurate values of material properties have to be given as input in ANSYS program. Modeling of steel material in FE is simple. The bilinear strain-stress curves is considered for steel in this study. The tendons are considered as multi linear isotropic material in this study.

3. Analysis of Plate Steel Girder

The proposed method for FE analyses was verified based on the results of plate girder ultimate load capacity tests are carried out in the laboratory of the University of Ljubljana, described in detail in Sinur [11]. The tested girders were designed so that they would fail because of high shear and/or the interaction of shearing forces and bending moments. The symmetric plated girder with close stiffener (SC) was chosen.

In Figure 1 the tested panels are noted. The length of the tested girder was 11.160 m. The tested girder with symmetric cross-section as shown in Figure 1 with total height of 1544 mm panels SC was tested.

The center of the longitudinal stiffeners was in the compression zone of the web, 350 mm from the upper flange. The web in the part of the tested panels SC (Figure 1) was 7 mm thick, which resulted in global slenderness of Wh/Wt=214. Double sided transverse flat stiffeners 156 × 20 mm was used to apply external load into a girder in the region of concentrated load. With additional transverse stiffeners at both ends of the girder, the rigid end post was assured [11].

The structure considered was loaded in such a way that forces and bending moments predominated and their combination would result in failure. Deformations within selected panel (SC) was analyzing in the particular phases of loading.

The FE mesh and boundary conditions of SC girder as shown in Figure 2. The SG is meshing after specifying the areas.

After modeling and analyzing the experimental model SC by ANSYS program, the load-mid-span deflection curves of the steel I-girder obtained from the FE analysis was compared with corresponding experimental data as shown in Figures 3. The results for load-deflection curves are validated and show good agreement with experimental results as shown in Figure 3.

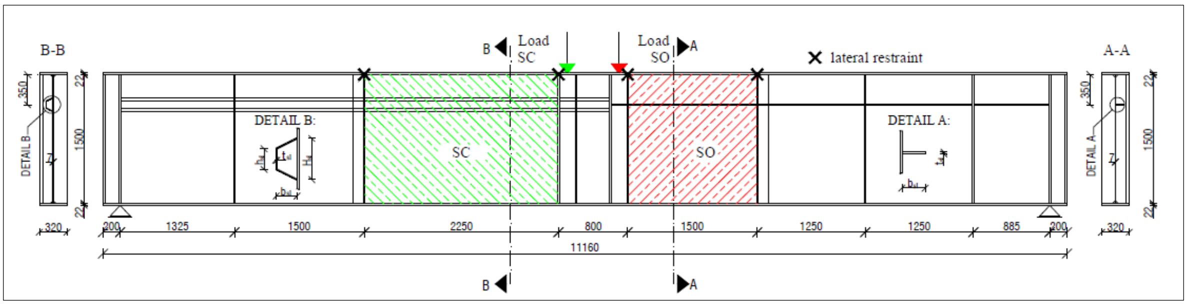

Figure 1. Girder geometry SC Specimen [11]

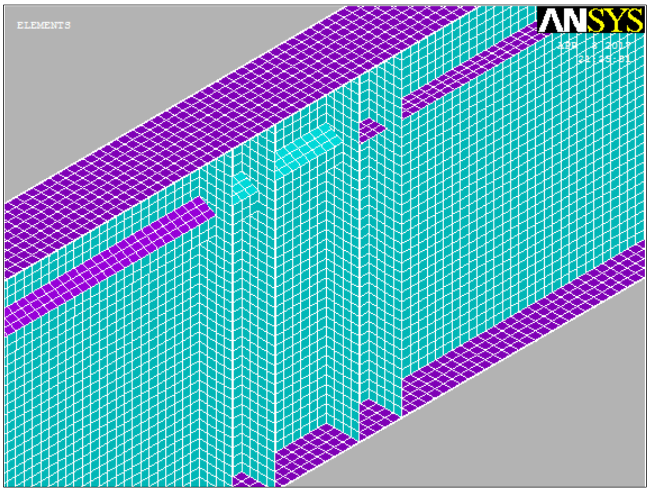

Figure 2. FE mesh and boundary conditions of SC girder

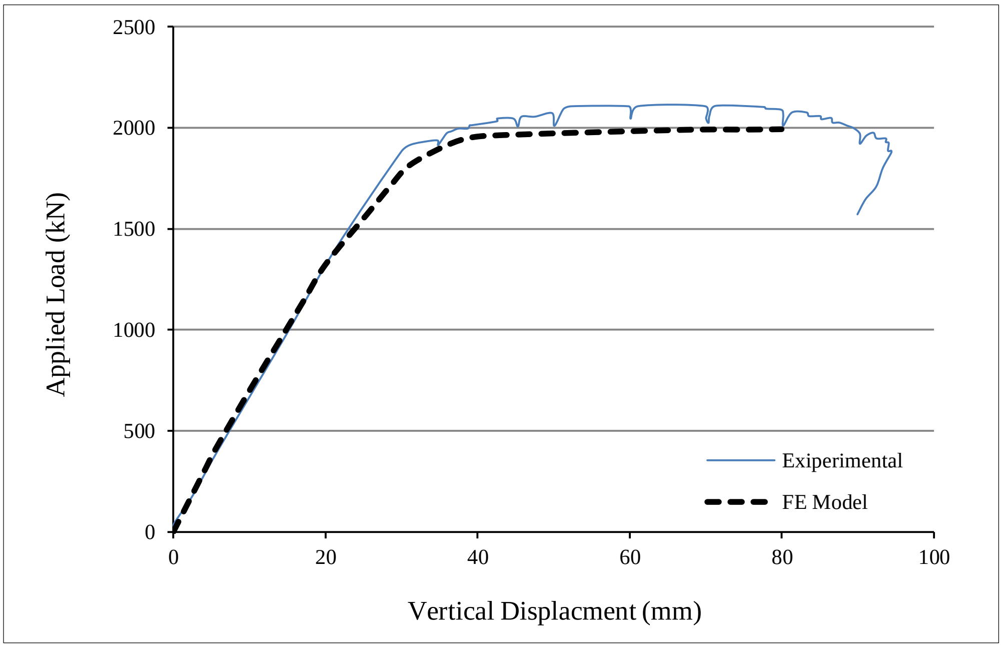

Figure 3. Load-deflection curves for the SC girder

4. Optimization of Steel Girder with External Prestressing

Numerous studies regarding the optimization of steel structure were available in literature. Little study were interested with the design optimization of SG with EP. In this paper, FE analysis is used to minimize the cross section of SG subjected to static loading.

The objective of the optimization method is to optimize the section area of SG while satisfying all applicable strength and serviceability limit states agreeing to the design code.

Two objective functions are considered in this study there are:

- Minimization of SE of the girder.
- Minimization of total volume of the girder.

Seven design variables are used in this study. The design variables are FW2, which is the width of bottom flange, FW1, which is the width of top flange, FT2, which is the thickness of bottom flange, FT1, which is the thickness of top flange, WH, that is the height of the web, WT, which is the width of the web and A, which is the area of the prestressing tendon as shown in Figure 4.

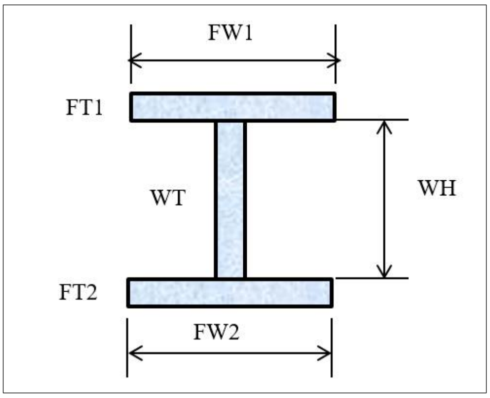

Figure 4. Cross section of girder

The constraints considered in this study are defined as follows:

- Maximum stress in steel.
- Maximum stress in steel tendons.
- Maximum shear stress in steel.
- Maximum deflection at mid-span of the steel girder.

The proposed SGs considered in this study are simply type support. The boundary.conditions was illustrated in Figure 5. The load was supplied as a concentratediload at mid.span and the total length of the SG is L = 23 m as shown in Figure 5.

In the FE analysis, the point load is distributed on the flange width to avoid numerical problems. The mesh of SG are illustrated in Figure 6.

The dimensions, loading, and boundary conditions considered for the modeling the SG are shown in Figures 5 and 6. The girder was subjected to two concentrated point load near the center and simply supported at ends. In the current study, using 3D solid elements, the SG was modeled.

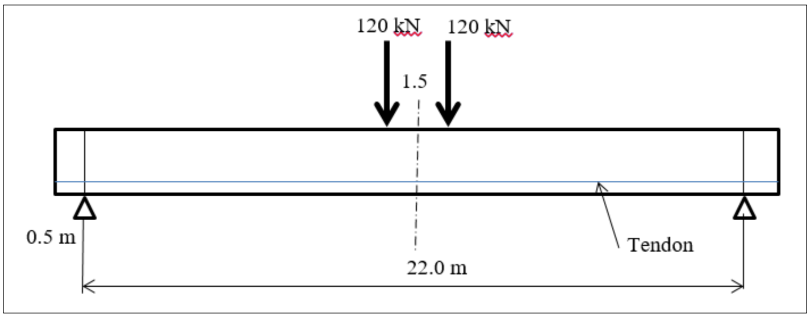

Figure 5. Geometry and loading for the proposed SG

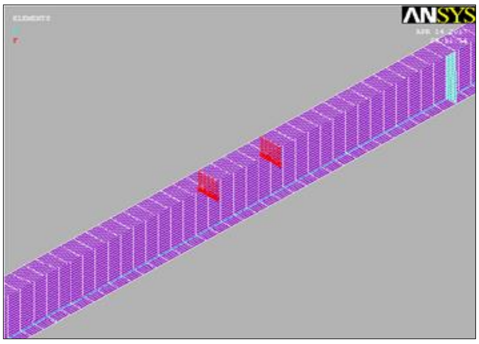

Figure 6. SG mesh

4.1. Optimization Strategy

In ANSYS package [20] 2-optimization procedures are presented: the sub problem approximation method and the first order method. The first-order procedure employs gradients of the dependent variables with respect to design variables. The sub problem approximation procedure could be described as a zero-order procedure that it requires only the variable values, and not requires their derivatives.

Optimization of SG is a thorough process in several steps that usually requires many iterations until a satisfactory design can be found. The designer is often free to choose a structural solution and vary different parameters. Formulating an optimization problem for complex tasks like this can be challenging, and it usually requires extensive numerical modeling [21].

The objective (size minimization) has a complex and implicit relationship with the design variables. This finite-element simulation is the most time-consuming part of the optimization.

4.2. Optimization of Steel Girder without External Prestressing

In this section the SG as shown in Figure 5 is considered for the optimization using two objective function which are the total volume and SE and the constraints are compression stress, tension stress and deflection.

Figure 7 shows the evolutioniof optimal WH versus.number ofiiterations for the SG without EP. From this figure, it can be found that the values of WH for the SE optimization is greater than values for the volume optimization.

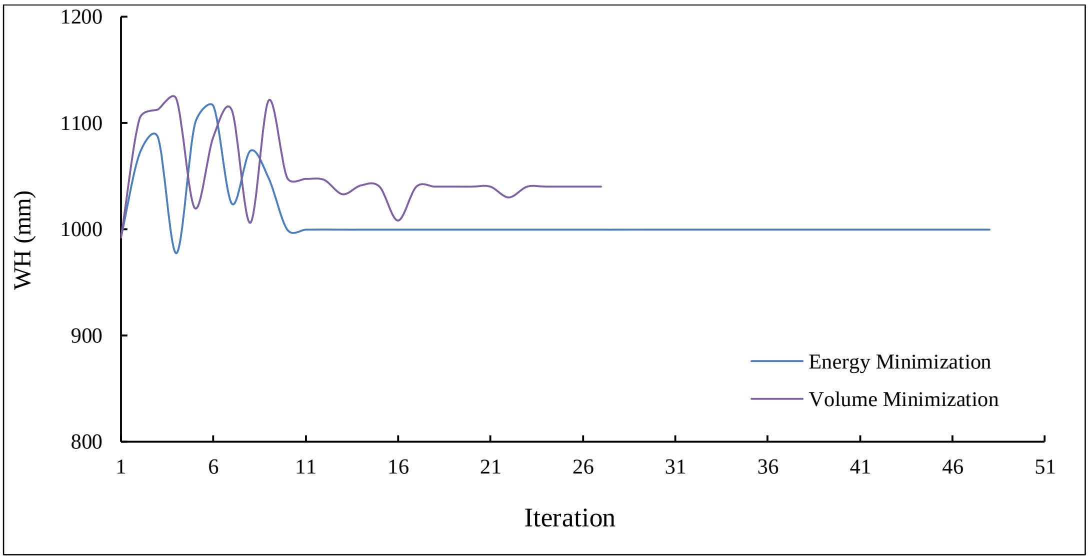

Figure 7. Evolution of optimal WH versus number of iterations for the SG without EP

Tables 1 and 2 show the result of the initial and optimum of design variables for volume and SE minimization of the SG without EP respectively.

From Tables 1 and 2, can be noticed to minimize the SE need to increase the width of bottom flange (FT2) and at result decrease the tension stress at bottom.

Table 1. Initial, optimum and limits of design variables and constraints for the volume minimization of the SG without EP

		Minimum	Initial value	Maximum	Optimum
Objective function	Volume (m^3)	----	790372000	---	718589000
Design variables (mm)	FT1 (mm)	16	23	36	24.1
	FT2 (mm)	16	23	36	24.2
	FW1 (mm)	370	402	430	422
	FW2 (mm)	370	402	430	410
	WT (mm)	10	16	20	11
	WH (mm)	900	992	1150	1040
Constraints	Max. fc (MPa)	-200	-191.12	0	-190
	Max. ft (MPa)	0	101.34	200	175.54
	Max. U_y (mm)	0	47.23	75	63.34

Table 3 shows the comparison of optimum values of design variables for optimization of the SG without EP for two objectives functions. From this table, it can be noted the value of optimum cross section area for the volume minimization is smaller than the value for SE minimization by 10.5 %. This is because the width of the top flange, the thickness of the top flange, the width of the bottom flange and the height of the web are smaller.

Table 2. Initial, optimumiand limits of design variablesiand constraints for the SE minimization of the SG without EP

		Minimum	Initial value	maximum	Optimum
Objective function	SE (Nmm)	----	6746848	---	6146333
Design variables (mm)	FT1(mm)	16	23	36	21.1
	FT2 (mm)	16	23	36	36.6
	FW1 (mm)	370	402	430	403
	FW2 (mm)	370	402	430	429.5
	WT (mm)	10	16	20	10.7
	WH (mm)	900	992	1150	999.5
Constraints	Max. *fc* (MPa)	-200	-191.12	0	-190
	Max. *ft* (MPa)	0	101.34	200	100.5
	Max. U_y (mm)	0	47.23	75	50.4
volume	Volume (mm^3)	---	790372000	---	803068000

Table 3. Comparison of Optimum.values of design.variables and constraints for the SG without EP

	FT1 (mm)	FT2 (mm)	FW1 (mm)	FW2 (mm)	WT (mm)	WH (mm)	Area of section (mm²)	Volume %	SE %
Volume minimization	24.1	24.2	422	410	11	1040	31243	9	-
SE minimization	21.1	36.6	403	429.5	10.7	999.5	34916	-	8.9

4.3. Optimization of Steel Girder with External Prestressing

In this section the SG as shown in Figure 5 is considered for the optimization using two objective function which are the total volume and SE and the constraints are compression stress, tension stress and deflection.

Figure 8 shows the evolution of optimal FW1 versus number of iterations for the SG with EP. From this figure, it can be noted the values of FW1 is equal until iteration (11) after that the optimum FW1 was smaller for the volume minimization.

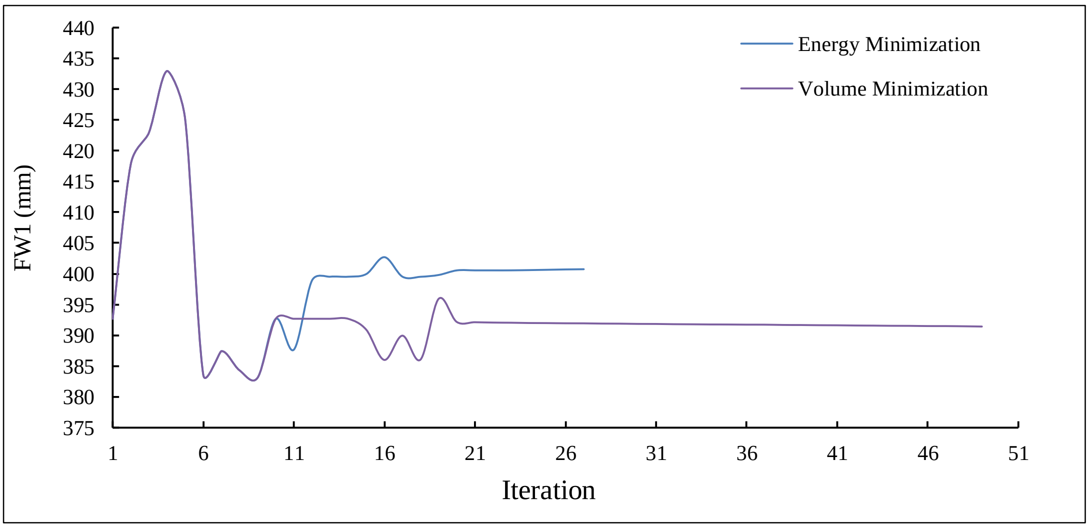

Figure 8. Evolution of optimal FW1 versus number of iterations for the SG with EP

Figure 9 shows the evolution of optimal WH versus number of iterations for the SG with EP. From this figure, it can be noted the values of WH is equal until iteration (10) after that the optimum WH was smaller for the volume minimization.

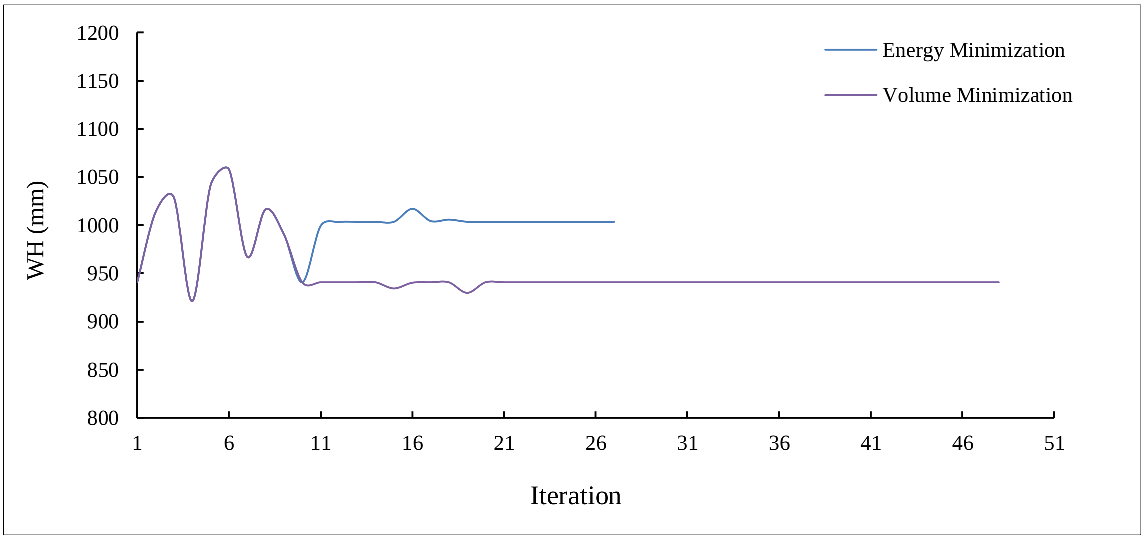

Figure 9. Evolution of optimal WH versus number of iterations for the SG with EP

Tables 4 and 5 show the results of the optimum and initial of design variables for the volume and SE minimization of the SG with EP respectively. From Tables 1-2, it can be noticed the optimum values of tension stress (*ft*) for total volume minimization is higher compared with SE minimization.

Table 4. Initial, optimum and limitsiof design variablesiand constraints for the volume minimization for the SG with EP

		Minimum	Initial value	maximum	Optimum
Objective function	Volume (mm³)	----	769326000	---	615679640
Design variables (mm)	FT1 (mm)	16	22.3	36	22.6
	FT2 (mm)	16	22.8	36	20.8
	FW1 (mm)	370	402	430	391. 8
	FW2 (mm)	370	403	430	390. 8
	WT (mm)	10	15.6	20	10.4
	WH (mm)	900	975	1150	940.9
	A (mm²)	125	150	175	130.3
Constraints	Max. *fc* (MPa)	-200	-186.3	0	-193.4
	Max. *ft* (MPa)	0	117.9	200	147.2
	Max. f_{tendon} (MPa)	0	1179.36	1430	1245
	Max. U_y (mm)	0	48.0584	75	59.2

Table 5. Initial, optimumiand limits.of design variablesiand.constraints for the SE minimization for the SG with EP

		Minimum	Initial value	Maximum	Optimum
Objective function	SE (Nmm)	----	3156594	---	2426802
Design variables (mm)	FT1 (mm)	16	22.3	36	21.2
	FT2 (mm)	16	22.8	36	35.7
	FW1 (mm)	370	402	430	401
	FW2 (mm)	370	403	430	429.5
	WT (mm)	10	15.6	20	11.5
	WH (mm)	900	975	1150	1003.4
	A (mm²)	125	150	175	131.3
Constraints	Max. *fc* (MPa)	-200	-186.3	0	-199.5
	Max. *ft* (MPa)	0	117.9	200	84.8
	Max. f_{tendon} (MPa)	0	1179.36	1430	1235
	Max. U_y (mm)	0	48.0584	75	43.8
volume	Volume (mm³)	----	769326000	----	813589350

Table 6 shows the comparison of optimum values of design variables for optimization of SG with EP. From this table, it can be noted the minimizing volume gives the less values for area of sections as compared with the results of SE minimization. However, by minimizing the energy, it found the area of section increase about 32 % compared with volume minimization, that due to the thickness of bottom flange (FT2), width of bottom flange (FW2), width of top flange (FW1) and the height of web (WH) are increased.

Table 6. Comparison of Optimum values of design variables and constraints for the SG with EP

	FT1 (mm)	FT2 (mm)	FW1 (mm)	FW2 (mm)	WT (mm)	WH (mm)	A (mm²)	Area of section (mm²)	Volume %	SE %
Volume minimization	22.6	20.8	391.8	390.8	10.4	940.9	130.3	26769	20	-
SE minimization	21.2	35.7	401	429.5	11.5	1003.4	131.3	35373	-	23

After optimization a different design.of the SG with prestressing achieved because the area of section is reduced. Figure 9 show a comparison of the FE load versus displacment curves of the SG with prestressing after optimization for the two objective functions. It is obvious that the failure load of the.optimized SG with prestressing for the volume minimization is higher.

At the maximum mid.span deflection, the faliure load for the SG with deflection minimization was found to be 883 kN against 833 kN and 864 for the volume and SE minimization respectively.

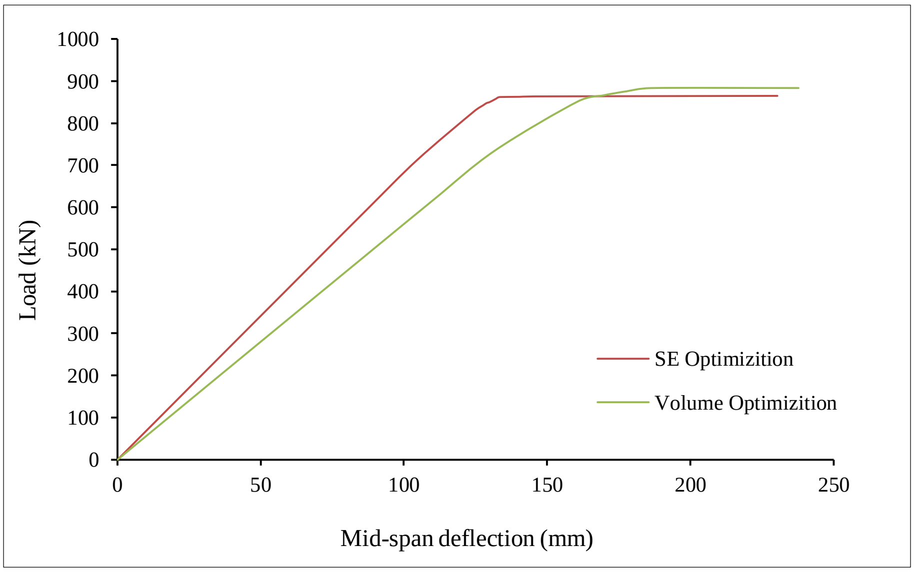

Figure 9. Load-deflection curve for the SG with prestressing after optimization for the different objective functions

4.4. Comparison of Optimization Results

Table 7 shows the comparison of optimum values of design variables for optimization of SG for the effect of prestressing. From this table, it can be noted the minimizing volume for the SG with prestressing gives the less values of area of sections as compared with the volume minimization for the SG without EP. It found the optimum area section for SG with prestressing was decrease about 14.3 % because the height of the web is decrease.

From this table, it can also be noted the minimizing strain energy for the SG with prestressing gives the less values of area of sections as compared with the strain energy minimization for the SG without EP. It found the optimum area section for SG with prestressing was smaller about 1.3 % than the optimum area of section for SG without prestressing.

Table 7. Comparison of optimum values of design variables and constraints for the effect of prestressing

	Case	FT1 (mm)	FT2 (mm)	FW1 (mm)	FW2 (mm)	WT (mm)	WH (mm)	A (mm²)	Area of section (mm²)
Volume minimization	with prestressing	22.6	20.8	391.8	390.8	10.4	940.9	130.3	26769
	Without prestressing	24.1	24.2	422	410	11	1040	----	31243
SE minimization	with prestressing	21.2	35.7	401	429.5	11.5	1003.4	131.3	35373
	without prestressing	21.1	36.6	403	429.5	10.7	999.5	----	34916

5. Conclusion

In this study, 3-dimensional FE model was presented using ANSYS to study the optimum design of steel girder with EP. Steel I-girder from literature was select for FE analyses verification, and good agreement was achieved between FE and test results. The optimum size of girder was calculated. ANSYS optimization procedures use three types of variables that describe the design optimization procedure: constraints, design variables, and the objective function. ANSYS APDL characterizes these variables by parameters. The use of APDL is an important step in the optimization procedures.

This research focused on the optimization of the steel I-girder with EP. Two objective functions are considered in this study there are minimization of SE and total volume of girder. Based on the FE analysis and optimization for the SG, the following conclusions can be stated:

- The results shows that the optimum section for the volume minimization smaller than for SE minimization for SG with EP tendons because the thickness of the bottom flange (FT2) , the width of the top flange (FW1), the width of the bottom flange (FW2) and the height of web (WH) decrease.
- The results shows that the optimum cross section for the SE minimization for SG with prestressing smaller than for SG without prestressing.
- The optimum volume for the SG with EP for volume minimization was smallest than SE minimization.
- It can be noticed the optimum values of tension stress (ft) for total volume minimization is higher compared with SE minimization.
- It is obvious that the controlled load of the optimized SG with prestressing for the volume minimization is higher for the SE minimization.

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