CHAPTER 5

GSO-assisted shape optimization of steel–concrete–steel sandwich beams

5.1 Introduction

Sandwich structures, also known as composite sandwich panels, are a type of construction material that consists of multiple layers of materials bonded together. The layers are typically arranged in a sandwich-like configuration, with a core material sandwiched between two outer skins or facings. The core material is usually a comparatively lightweight and strong material, such as foam, honeycomb or concrete while the outer skins are typically made of a stronger and more durable material, such as metal or composite fibres. One of the main advantages of sandwich structures is their combination of strength and lightweight construction. The core material provides a high level of strength and stiffness, while the outer skins provide the necessary durability and protection. This allows sandwich structures to be used in a wide range of applications, from aerospace and transportation to construction and marine industries. Sandwich structures are also highly customizable, as the core and outer skins can be made from a wide variety of materials. This allows for the optimization of the structure for specific needs, such as fire resistance, insulation, or environmental resistance.

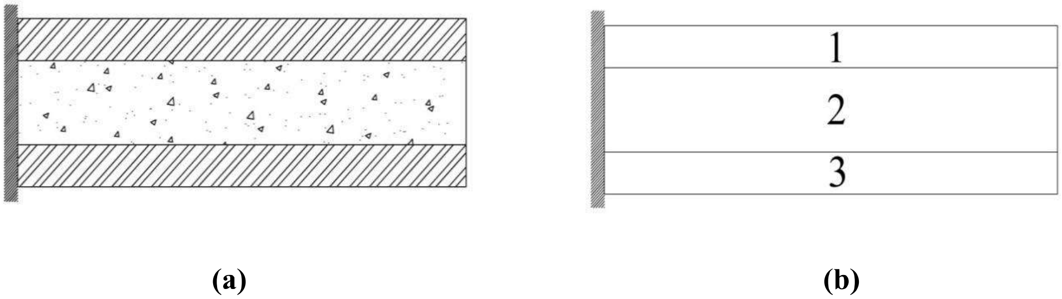
Steel-concrete-Steel (SCS) sandwich structures are a type of composite sandwich panel that consists of a concrete core sandwiched between two steel outer skins. A steel-concrete-steel (SCS) sandwich beam is made up of two steel faceplates of the thickness (t_f) sandwiching a concrete core of thickness (t_c) generally abiding by the ratio of $t_f/t_c \ll 1$, connected via mechanical connectors forming a compact unit to withstand externally applied loads. These structures are gaining popularity in the construction industry due to their high strength, durability and fire resistance properties. They are also known as composite steel-concrete structures, steel-concrete composite structures or steel-concrete hybrid structures. The steel outer skins of SCS sandwich structures provide a high level of strength and stability, while the concrete core provides fire resistance and thermal insulation in addition to strength. The steel and concrete layers are bonded together through the use of mechanical fasteners, such as shear studs or headed studs, or through the use of adhesives. This allows for a strong and stable connection between the two materials, creating a composite structure that is stronger than either steel or concrete alone. One of the main advantages of SCS sandwich structures is their high strength-to-weight ratio. The steel outer skins provide a high level of strength, while the concrete core provides additional strength, weight and stability. This allows for the construction of taller and more slender buildings, as well as structures with larger spans and smaller cross-sections. Additionally, SCS sandwich structures are also highly customizable, as the concrete core can be made from a wide variety of materials, such as lightweight concrete, normal-weight concrete or high-strength concrete, depending on the specific requirements of the project.

Optimization of SCS sandwich structures is the process of designing and selecting the most efficient and cost-effective combination of materials and structural elements to achieve the desired performance criteria. This includes the selection of the optimal thickness and properties of the steel and concrete layers, as well as the selection of the most appropriate type and configuration of mechanical fasteners or adhesives used to bond the steel and concrete layers together. As discussed in Chapter 2 two main criteria have been focused on by researchers when optimizing SCS sandwich structures: the minimization of core density and the reduction of the thickness of the face and core. The core density is reduced by using lightweight materials such as foam or honeycomb, while the thickness of the outer skins and core is reduced by using thinner materials or by increasing the strength of the materials used. However, almost all of the research and its application have pinned up to the idea of having a constant face and core thickness. This is because the traditional fabrication techniques were not able to produce sandwich elements with non-uniform cross-sections. But with the advent of modern and improved fabrication techniques, the demand for using lighter weight design intensifies, and sandwich elements with non-uniform cross-sections will likely be used. One of the effective ways to reduce the weight of SCS sandwich structures is to reduce the amount of steel used and replace it with concrete. The weight density of steel (around 7750 kg/m^3) is very high compared to concrete (around 2500 kg/m^3), therefore reducing the amount of steel and replacing it with concrete can serve the purpose of a lighter-weight SCS sandwich beam. However, this should be done in a way that the structural integrity and service-ness of the structure are not hampered.

The present work draws inspiration from previous studies that have successfully utilized GSO software for shape optimization. It proposes a new approach that involves altering the shape of the faceplates and core at the interface using GSO software. The primary objective of this approach is to reduce the amount of steel used and increase the amount of concrete without impacting the overall shape of the beam. The end result is a lighter weight SCS sandwich beam that maintains structural integrity and serviceability.

5.2 Model generation and optimization

The SCS structure subjected to optimization is first partitioned into the required number of design elements, and then each of these design elements is characterized by a set of keynodes or master nodes, which is responsible for controlling the geometry of design elements. It should be taken into account that the discretization of the SCS sandwich beam is different from that of a normal beam used in Chapter 3. However, the elements used are the same 9-noded lagrangian elements. Figure 5.1 shows the discretization of the SCS sandwich beam.



(a) **(b)**

Figure 5.1: **(a)** SCS sandwich cantilever beam **(b)** Division of the model into design elements 1, 2, and 3.

5.2.1 Fuzzy membership function

As in the zero-order method for shape optimization, the modification of geometry is greatly dependent upon the value of stress at boundary nodes. The geometry is modified at each iteration taking into consideration the value of maximum shear stress at design nodes in the previous iteration. Here the criterion of maximum shear stress (σ) being lesser than or equal to the target maximum shear stress (σ_t) is fulfilled when the value of σ at each design node is almost equal to the σ_t value. Taking the objective to find the shape for which the σ value is nearest to the σ_t value, the concept of the fuzzy membership function is used. Herein also, for this study, the use of the triangular shape membership function is done.

When σ is greater than σ_t, the material there is added and when σ is lesser than σ_t, the material there is subtracted in each iteration until the value of both σ at design nodes and σ_t become more or less equal. This approach is incorporated using the same fuzzy membership concept taking in the i^{th} node movement to be proportionate to the move factor (MF). In the present study, the difference allowed between the values of σ and σ_t is less than or equal to 0.01 N/mm^2 The nodal movement of nodes in the study has been allowed as one-tenth of the full-length movement of L_{min}. Therefore, the movement of design nodes is represented by Equation 5.1:

$$\text{MV}(i) = 0.1 \cdot L_{min} \cdot \text{MF} \tag{5.1}$$

5.3 Problem formulation

The present study takes into account a targeted stressed design, with stress being optimized at the design nodes. The concrete as presented in section 5.2, is modelled as a discretized continuum using nine-noded lagrangian element. The structural elements are analysed using finite element analysis (FEA). Since the process focuses on getting as near to the target stress for the given SCS sandwich beam, the objective function to be minimized or maximized is stress σ_i at the design nodes such that it becomes more or less equal to σ_t with a tolerance of up to 0.01 N/mm^2. The value of σ_t can be changed as per the requirement of the user. To fulfil this objective, the design variable selected is design-node/s of concrete which will move to change the shape as explained in section 5.2.1. Another restriction on the permitted amount of deflection (δ) is also provided to ensure that the optimized shape has a regulated deflection. The convergence is achieved using the formulation as explained in Chapter 3 section 3.3.4. The overall optimization problem for the present study can be formulated mathematically using Equation 5.2.

$$\text{Minimize/Maximize} \quad \sigma_i \ (\forall\ \mathrm{i} = 1 \text{ to } \mathrm{n}) \tag{5.2}$$

$$\text{Such that} \quad \begin{cases} \sigma_i \leq \sigma_t \pm 0.01\ \mathrm{N/mm^2}\ (\sigma_t \text{ can be decided as per the user requirements}) \\ \text{Deflection } (\delta) \leq \text{Minimum } (Span/250,\ 20\ \mathrm{mm}) \end{cases}$$

Where n is the total number of design nodes.

5.4 Validation study

In order to optimize SCS sandwich beams, it is essential that the software is capable of accurately analyzing such structures. To verify the accuracy of the GSO software, a validation study was conducted, in which the results for interfacial shear stress and deflection obtained from the software were compared to those from a previous experimental study conducted by Solomon et al. (1976). In their study, Solomon et al. designed various types of SCS sandwich beams with varying thicknesses of the core and faceplates, and evaluated their performance in terms of collapse load and deflection. They also calculated the interfacial shear stress between the steel face and the concrete core, but they only reported the deflection results for Beam 5 and Beam 11. Table 5.1 presents a comparison of the results obtained by Solomon et al. and the GSO software for SCS sandwich beams.

Table 5.1: A comparison study of GSO with experimental results obtained by Solomon et al. (1976) for interfacial shear stress and central deflection of different beams.

Beam	**B 3**	**B5**	**B 11**	**B 12**	**B 15**	**B 17**
Length (mm)	2000					
Width (mm)	150			300	150	
Core depth (mm)	75	90	90	90	100	105
Plate thickness (mm)	3.18				4.76	
$E_{concrete}$ (kN/mm^2)	34.1	34.7	34.3	34.2	34.4	31.6
E_{steel} (kN/mm^2)	210	230	207	228	227	222
Shear Span (mm)	225	90	750	150	750	750
Collapse Load (kN)	45	195	42.3	145	46.6	45
Interfacial shear stress (N/mm^2) Solomon et al.	1.21	4.19	0.89	1.56	1	0.92
Present interfacial shear stress (N/mm^2)	1.57	4.37	0.94	1.59	1.17	1.04
Central deflection (mm) Solomon et al.	-	5.49	7.72	-	-	-
Present central deflection (mm)	1.89	5.57	7.44	1.19	5.14	4.41

From Table 5.1, it can successfully be inferred that the results obtained by the present GSO software are in good agreement with those obtained by Solomon et al. and henceforth can be utilized for the analysis of stress and deflection of SCS sandwich beams.

5.5 Numerical Illustration

Using the proposed approach compiled in the GSO software, a few examples of shape optimization of SCS sandwich beams are done. Young's modulus for the steel plates is taken as 2 x10^5 N/mm^2, and the concrete core is taken as 2x10^4 N/mm^2. The weight density of steel is taken as 7900kg/m^3 and concrete is taken as 2400 kg/m^3. The dimension applied live load and type of beam are presented in Table 2. In all the beams, three design elements were taken into account with the help of suitable design nodes. The fixed cantilever beam was divided into 36 Lagrangian plane stress elements with nine nodes in each, leading to a total of 169 nodes. On the other hand, the fixed and simply supported beams were split into 48 Lagrangian plane stress elements, also with nine nodes each, resulting in a total of 221 nodes. Figure 5.2 provides a visual representation of the beam that was divided into 48 nine-noded Lagrangian elements. The value of σ_t in all the cases is taken as 0.3 N/mm^2 (as per the criteria of design shear strength of concrete without reinforcement in accordance to design code IS 456:2000). The initial shape of the straight and curved SCS sandwich beam is depicted in Figure 5.3 and the system time taken, and the number of iterations in each case to get the optimized shape, along with the central deflection before and after optimization, are shown in Table 5.2. The optimized shape obtained and σ distribution in each case are shown in Figure 5.4 and Figure 5.5, respectively.

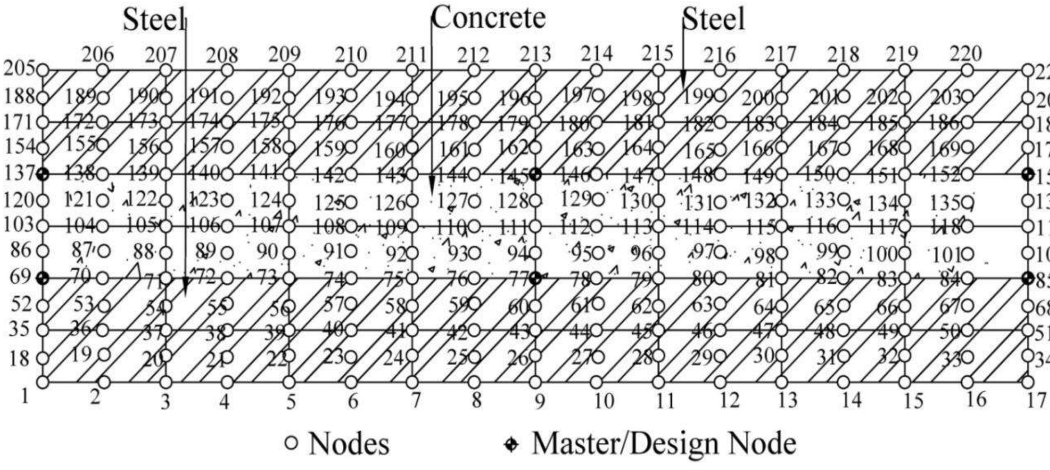
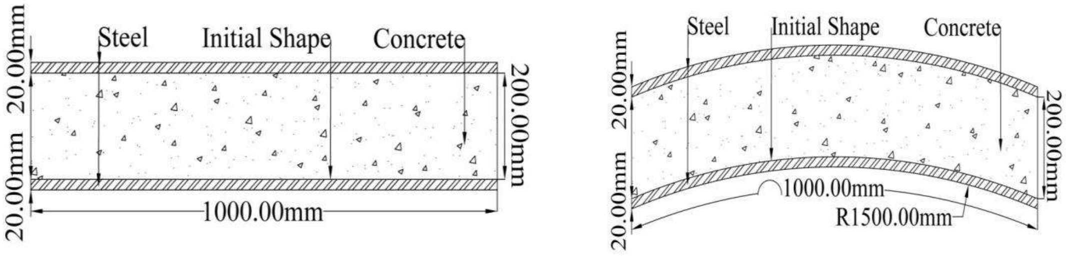


Figure 5.2: Discretization of Sandwich beam

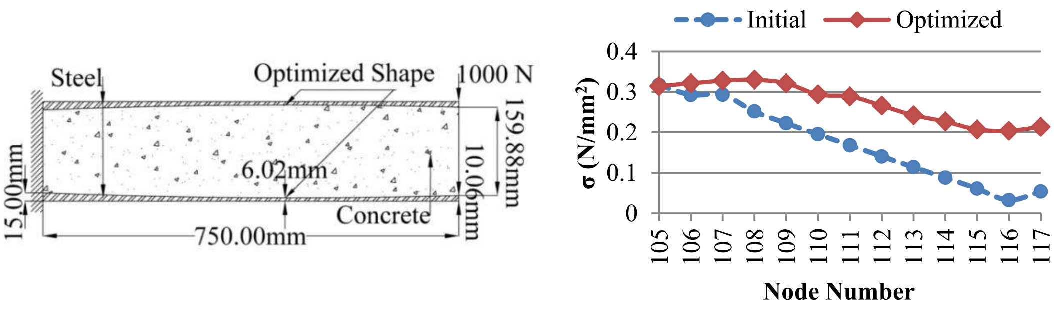


(a) (b)

Figure 5.3: (a) Initial Shape of Straight SCS sandwich beam, **(b)** Initial Shape of Curved SCS sandwich beam

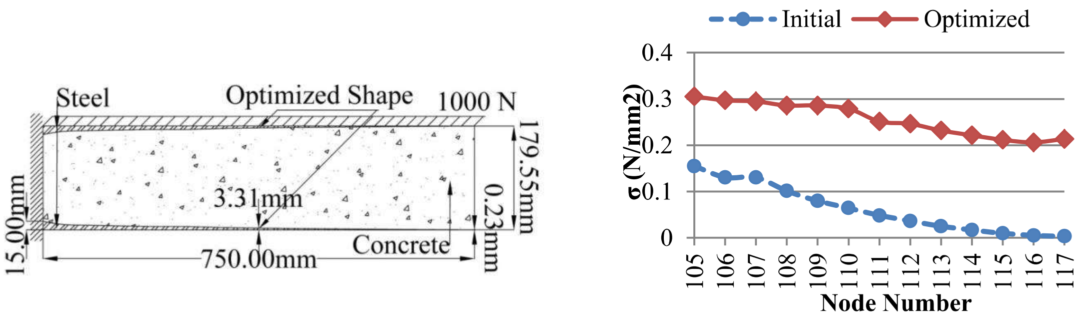
Table 5.2: Parameters for different sandwich beams with iterations and time required to get the optimized shape along with overall central deflection.

Support Condition	**Type of Loading**	**Type of Sandwich Beam**	**Live Load (N)**	**Position of Loading**	**Dimension (mm) L=Length, B=Breadth, D=Overall Depth (Face sheet, Core, Face sheet)**	**No. of Iteration to reach the optimized shape**	**System time taken to reach the optimized shape (sec.)**	**Central deflection before optimization (mm)**	**Central deflection after optimization (mm)**
Fixed Cantilever	Point Load	Straight	1000	At the free end	L=750, B=200, D=180 (15,150,15)	537	69.41	$0.867\mathrm{x}10^{-2}$	$0.947\mathrm{x}10^{-2}$
	Uniformly Distributed Load	Straight	1000	Along the length	L=750, B=200, D=180 (15,150,15)	946	109.32	$0.563\mathrm{x}10^{-2}$	$0.587\mathrm{x}10^{-2}$
Simply Supported	Point Load	Straight	7000	At midpoint	L=1000, B=300, D=240 (20,200,20)	117	15.99	$0.107\mathrm{x}10^{-1}$	$0.110\mathrm{x}10^{-1}$
		Curved	4000	At midpoint	L= ⌒1000, B=200, D=240 (20,200,20)	162	23.15	$0.102\mathrm{x}10^{-1}$	$0.108\mathrm{x}10^{-1}$
	Uniformly Distributed Load	Straight	7000	Along the length	L=1000, B=300, D=240 (20,200,20)	262	31.82	$0.719\mathrm{x}10^{-2}$	$0.801\mathrm{x}10^{-2}$
		Curved	4000	Along the length	L= ⌒1000, B=200, D=240 (20,200,20)	312	43.65	$0.722\mathrm{x}10^{-2}$	$0.879\mathrm{x}10^{-2}$
Fixed	Point Load	Straight	7000	At midpoint	L=1000, B=300, D=240 (20,200,20)	331	44.25	$0.483\mathrm{x}10^{-2}$	$0.559\mathrm{x}10^{-2}$
		Curved	4000	At midpoint	L= ⌒1000, B=200, D=240 (20,200,20)	436	57.60	$0.376\mathrm{x}10^{-2}$	$0.468\mathrm{x}10^{-2}$
	Uniformly Distributed Load	Straight	7000	Along the length	L=1000, B=300, D=240 (20,200,20)	476	63.07	$0.262\mathrm{x}10^{-2}$	$0.340\mathrm{x}10^{-2}$
		Curved	4000	Along the length	L= ⌒1000, B=200, D=240 (20,200,20)	736	98.61	$0.204\mathrm{x}10^{-2}$	$0.263\mathrm{x}10^{-2}$



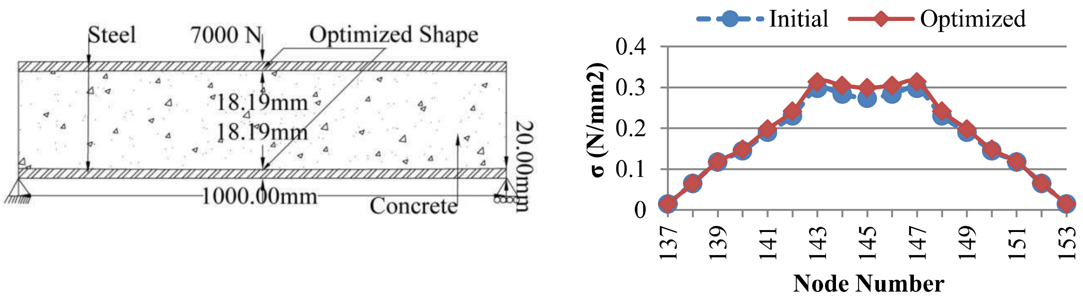
(a) **(b)**

Figure 5.4(a). Fixed cantilever SCS sandwich beam with point load **(b).** Shear stress distribution in fixed cantilever SCS sandwich beam having a point load



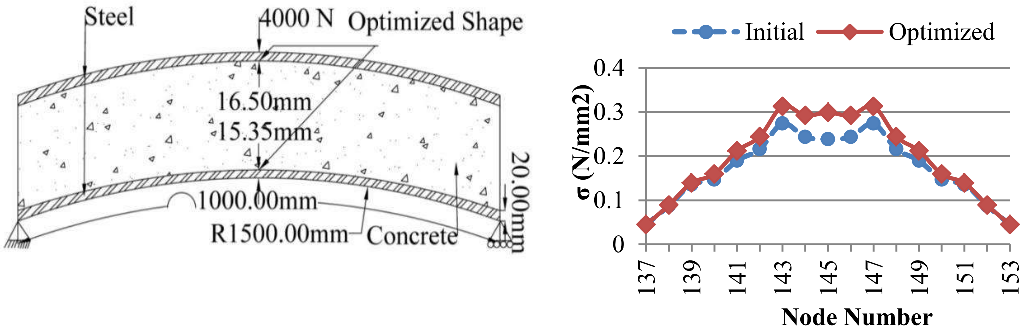
(c) **(d)**

Figure 5.4(c). Fixed cantilever SCS sandwich beam with uniformly distributed load **(d)** Shear stress distribution in fixed cantilever SCS sandwich beam having a uniformly distributed load



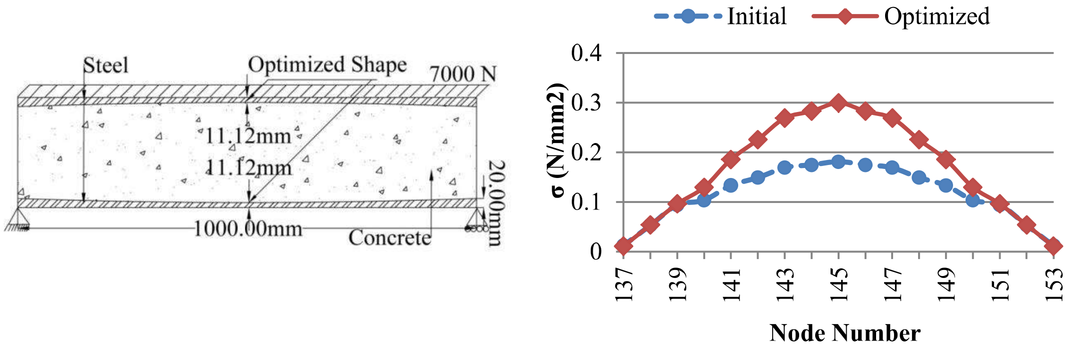
(e) **(f)**

Figure 5.4(e). Simply supported straight SCS sandwich beam with point load **(f)** Shear stress distribution in simply supported cantilever SCS sandwich beam having a point load



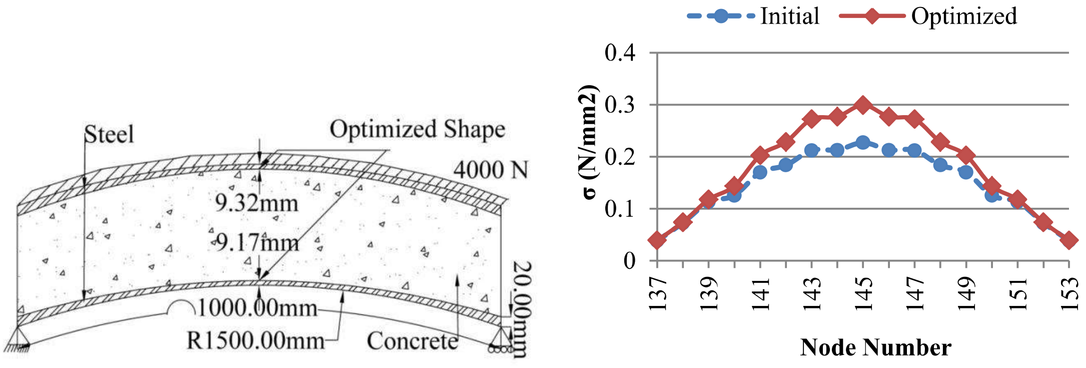
(g) **(h)**

Figure 5.4(g). Simply supported curved SCS sandwich beam with point load **(h)** Shear stress distribution in simply supported curved SCS sandwich beam having a point load



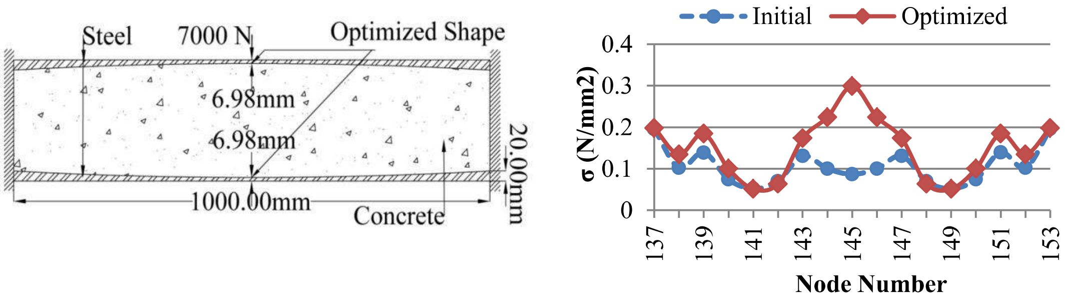
(i) **(j)**

Figure 5.4(i). Simply supported straight SCS sandwich beam with uniformly distributed load **(j)** Shear stress distribution in simply supported straight SCS sandwich beam having a uniformly distributed load



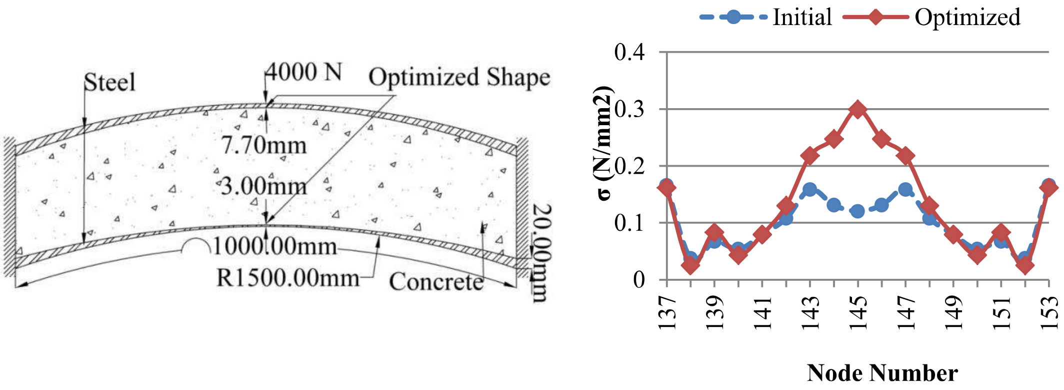
(k) **(l)**

Figure 5.4(f). Simply supported curved SCS sandwich beam with uniformly distributed load **(l)** Shear stress distribution in simply supported curved SCS sandwich beam having a uniformly distributed load



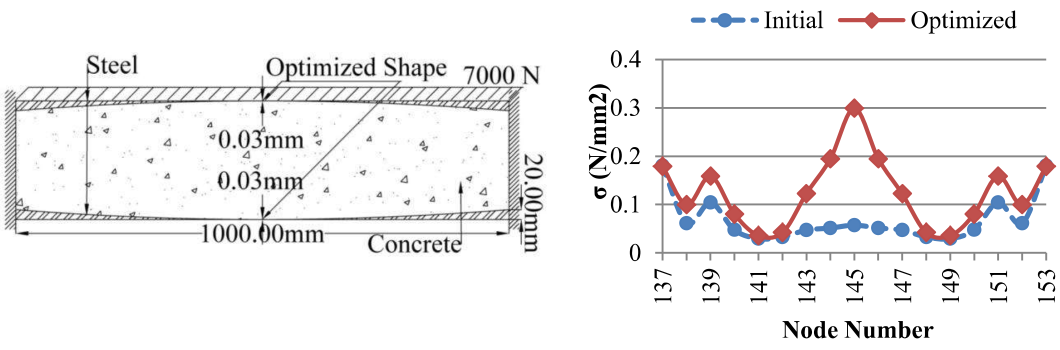
(m) **(n)**

Figure 5.4(m). Fixed straight SCS sandwich beam with point load **(n)** Shear stress distribution in fixed straight SCS sandwich beam having point load



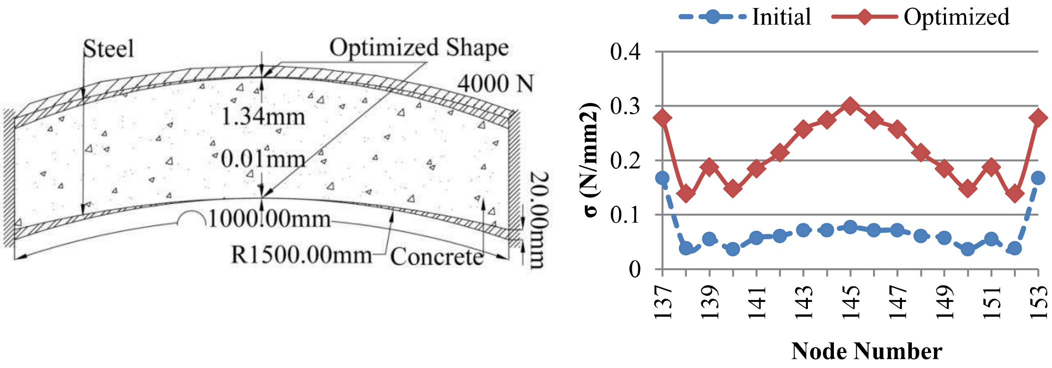
(o) **(p)**

Figure 5.4(o). Fixed curved SCS sandwich beam with point load **(p)** Shear stress distribution in fixed curved SCS sandwich beam having point load



(q) **(r)**

Figure 5.4(q). Fixed straight SCS sandwich beam with uniformly distributed load **(r)** Shear stress distribution in fixed straight SCS sandwich beam having uniformly distributed load



(s) **(t)**

Figure 5.4 (s). Fixed curved SCS sandwich beam with uniformly distributed load **(t)** Shear stress distribution in fixed curved SCS sandwich beam having uniformly distributed load

5.6 Discussion of results.

The results in section 5.5 show that GSO software is able to optimize SCS sandwich beams while meeting the requirement of maximum shear stress being less than or equal to the target value at any point. The results in Figure 5.4(a) and 5.4(c) show that the amount of steel removed from the faceplate in the case of a cantilever SCS beam under a concentrated load is less than that under a uniformly distributed load. This trend is also observed in simply supported straight and curved SCS beams as well as fixed straight and curved SCS beams. Additionally, the upper and lower face plates in straight SCS beams are optimized to similar thicknesses, while in curved SCS beams, they are optimized to different thicknesses due to non-linear stress distribution. For example, in Figure 5.4(o), the upper faceplate is optimized to a central thickness of 7.70mm, whereas the lower faceplate is optimized to a central thickness of 3.00mm. Furthermore, the results show that SCS sandwich beams with fixed support conditions are more optimized than those with simply supported support conditions for the same load, as fixed supported beams can take more load than simply supported beams. It can be concluded from the results in the previous section that the optimized SCS sandwich beams satisfy the serviceability condition, as the change in deflection before and after optimization is negligible (around 10^{-4}). In terms of the GSO software, it is observed that the number of iterations required to achieve the optimized shape is higher for a uniformly distributed load than a concentrated load. However, the number of iterations can be decreased by increasing the nodal movement of nodes from one-tenth of L_{min} to one-fourth or more, but this may slightly affect the accuracy of results. On average, each iteration takes approximately 1.406×10^{-1} seconds to complete.

5.7 Concluding remarks

The study presents a successful application of the fuzzy-based integrated zero-order method for shape optimization of Steel-Concrete-Steel (SCS) structures. The method effectively optimizes the shape of the interface between the core and the faceplate, reducing the amount of steel and increasing the amount of concrete, while maintaining the structural integrity and serviceability requirements for a given load on the beam. The resulting maximum stress (σ_{max}) is close to the assumed yield strength (σ_t) and does not exceed it. The optimization process is achieved using minimal design elements and proper design nodes, resulting in faster convergence without compromising the quality of results. The program has a low overall runtime and does not require high-end computing capabilities. The effectiveness of the GSO software based on the integrated zero-order approach is demonstrated through several examples shown in Figure 5.4. The proposed approach is found to successfully optimize the shape of SCS sandwich beams, and can be applied in industrial applications.