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Application of Column Buckling Theory to Steel Aluminium Foam

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Abstract:	In steel structures, a lot of attention is paid to lightweight structures, i.e. reduction of dead load without compromising structural safety, integrity and performance. Thanks to modern steel aluminium foam sandwich panel manufacturing technology a new possibility became available for lightweight structural design. Assessment and understanding of the behaviour of this sandwich panel under in-plane compression or flexure is crucial before its application in steel structures. Column buckling theory is considered and applied to the steel aluminium foam sandwich panel to evaluate its behaviour under in-plane compressive load. In this work, various assumptions are made to generalise Euler's buckling formula. The generalization requires modification of the buckling stiffness expression to account for sandwich panel composite properties. The modified analytical expression is verified with finite element simulation employing various material models specific to steel face-plates and aluminium foam as well as various geometric imperfections. Based on the study, it can be concluded that Euler's buckling formula can be successfully modified and used in the prediction of the load-carrying capacity of a sandwich panel.
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December 29th, 2022

Dear Editor,

we would like to submit the revised version of the manuscript entitled "Application of Column Buckling Theory to Steel Aluminium Foam Sandwich Panels".

The present research work aims at structural optimization of aluminium foam sandwich panels subjected to buckling loads. The present design procedure can be used in structural analysis for carrying out design of such structural components.

We think that the present research falls within the scope of Structures and the current Special Issue.

Thank you for your consideration.

Sincerely,
Nicholas Fantuzzi (on the behalf of all the other authors)

Application of Column Buckling Theory to Steel Aluminium Foam Sandwich Panels

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ABSTRACT

In steel structures, a lot of attention is paid to lightweight structures, i.e. reduction of dead load without compromising structural safety, integrity and performance. Thanks to modern steel aluminium foam sandwich panel manufacturing technology a new possibility became available for lightweight structural design. Assessment and understanding of the behaviour of this sandwich panel under in-plane compression or flexure is crucial before its application in steel structures. Column buckling theory is considered and applied to the steel aluminium foam sandwich panel to evaluate its behaviour under in-plane compressive load. In this work, various assumptions are made to generalise Euler's buckling formula. The generalization requires modification of the buckling stiffness expression to account for sandwich

panel composite properties. The modified analytical expression is verified with finite element simulation employing various material models specific to steel face-plates and aluminium foam as well as various geometric imperfections. Based on this study, it can be concluded that Euler's buckling formula can be successfully modified and used in the prediction of the load-carrying capacity of a sandwich panel.

1. INTRODUCTION

Bert, Noor and Burton state that the concept behind sandwich construction can be traced back to Fairbairn in England in 1849 (Vinson 2005). The first application of sandwich technology was in mosquito aircraft in England, which was used in the Second World War (Allen 2013). In the mosquito aircraft model, the sandwich construction with plywood was used. In 1969, the first successful landing of a spaceship on the moon took place (Herrmann et al. 2005) due to the application of various technologies such as rocket, aerospace, computer science and last but not least sandwich construction.

The most simple type of sandwich panel consists of two strong, stiff, thin plates or sheets of highly dense material separated by a thick layer of low-density material that can be much less strong and stiff (Allen 2013). Figure 1 gives a general idea of a sandwich panel. A lot of sandwich construction can be made based on structural requirements by combining different core and face materials. This possibility of combining materials makes it possible to make an optimum structure of the sandwich panel for specific applications. In sandwich panels, it is possible to combine the positive properties of individual materials. This freedom makes it possible to make a sandwich panel with various favourable properties such as high load-bearing capacity with low self-weight, capacity for rapid erection without heavy lift cranes or equipment, ease in installation and replacement or repair in case of damage and long life with a low maintenance cost. The payload can be raised, higher speeds can be reached and less fuel consumption can be obtained when using these lightweight materials (Crupi et al. 2011). Some of the other advantages of sandwich panels are the mass predictability, long-spanning capability, durability, pre-fabricability and finally yet importantly reusability. These characteristics justify the increasing demand and application of sandwich panels in various fields and industries.

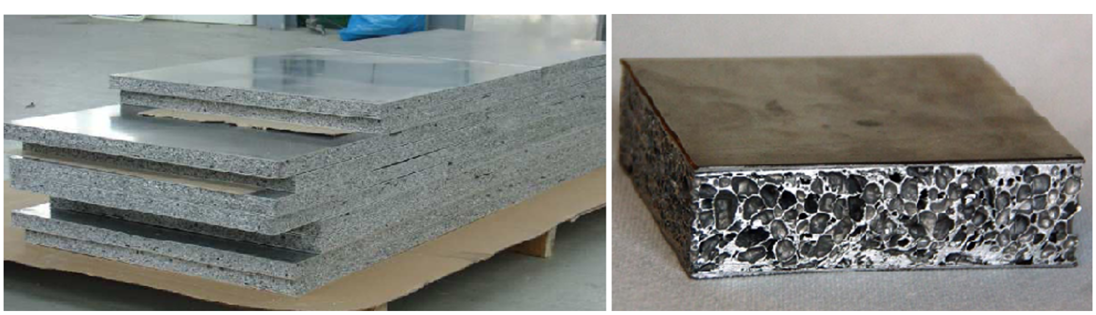


Fig. 1. Steel aluminium foam sandwich panel (Szyniszewski et al. 2012) (Foam 2016)

The buckling issues are often treated as a two-dimensional problem. Global buckling of a composite sandwich structure only occurs if the core is sufficiently stiff enough in the through-thickness direction (Daniel et al. 2002). If not then face wrinkling might occur. Buckling and wrinkling are the most common failure modes for the sandwich panel. These failure modes are the basis for design for most sandwich panels. Carlsson and Kardomateas (2011)(Carlsson and Kardomateas 2011) gave various theoretical approaches for sandwich buckling and Howard Allen (Allen 2013) did various research on these sandwich panels.

Face wrinkling is also known as local (short wavelength) buckling. Face wrinkling will occur when the critical value of compressive stress of the face-plate is reached. Face wrinkling can be of two types: symmetric and asymmetric. In certain cases, if the load on one face is more than the other or if the thickness of the faces is unequal then the face with more load or less thickness can buckle resulting in single-sided face wrinkling. Figure 2 gives a brief idea of sandwich panel buckling where 'L' is length, 'P' is axial compressive load, 'h_f' is thickness of face-plate and 'h_c' is thickness of core of the sandwich panel.

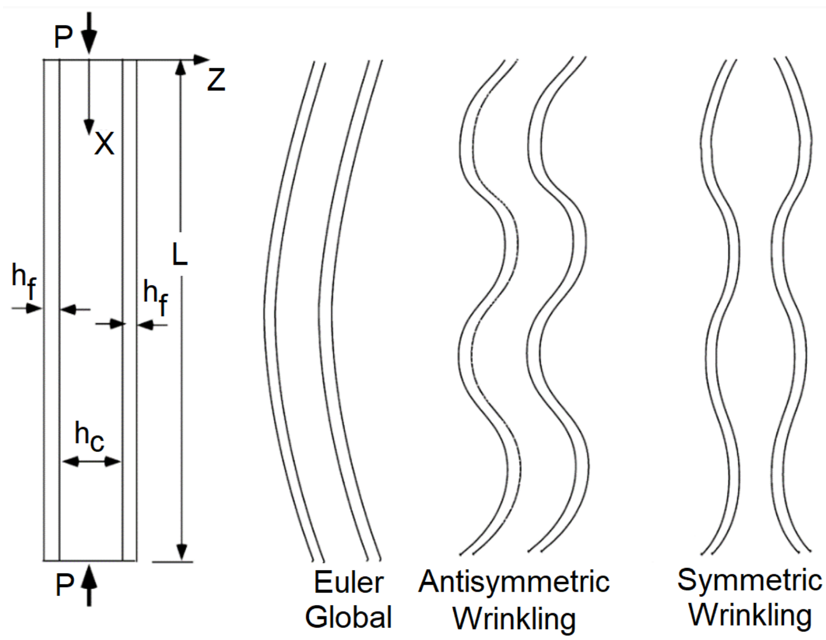


Fig. 2. Buckling modes (Carlsson and Kardomateas 2011)

Various research has been done by Gough GS(Gough et al. 1940), Goodier JN(Goodier and Neou 1951) and Hoff NJ(Hoff and Mautner 1945) on wrinkling problems of sandwich panels. However, as per Niu and Talreja(Niu and Talreja 1999), different researchers have given different results for the same wrinkling phenomenon. Some researchers did try to achieve a general method that can be applied for both the global buckling and wrinkling phenomenon. Benson and Mayers(Benson and Mayers 1967) were the first to suggest an approach for simultaneously solving global buckling and wrinkling questions. After the wrinkling model, Niu and Talreja(Niu 1998) proposed a combined model for both wrinkling as well as global buckling. Investigations are done by Léotoing(Léotoing et al. 2002) on wrinkling and global buckling of sandwich panels with unified expression. In this investigation, the core material is considered as a higher-order beam model. Numerical, analytical and experimental analysis is done by Jasion(Jasion et al. 2012) on wrinkling and global buckling of sandwich panels. The local buckling strength of steel foam sandwich panels has been studied by S Szyniszewski(Szyniszewski et al. 2012). In this study, a significant strength increment is observed for a sandwich panel of steel face-plates and steel foam as compared to a solid steel plate. Recently Douville(Douville and Le Grognec 2013) used a total Lagrangian formulation for postulating an exact analytical solution for both local and global buckling of sandwich panels under various loads. All of these proposed methods and theories are pretty tedious and long to be applied in the field.

For predicting the compressive strength of the FRP sandwich panel, a new empirical design approach is presented by Martin Noël and Amir Fam(Noel and Fam 2021). A simple design model which considers both global and local failure modes and can be used for design purposes is proposed in this study. Martin Noël and Amir Fam propose an empirical model which was calibrated by using 168 test results of the concentrically loaded sandwich panel made of FFRP or GFRP face sheet and polyurethane or polyisocyanurate rigid foam cores. FRP sandwich panels are becoming popular due to their lightweight, ease and speed of installation, and high thermal insulation capabilities. Kenneth Mak, Amir Fam and Colin MacDougall(Mak et al. 2015) tried to replace conventional GFRP skins with bio-based skins made from unidirectional flax fibers and a resin blend consisting of epoxidized pine oil. In this study, a 4-point bending test is done to predict the flexural strength of the sandwich panel. A new type of composite called Layered Sandwich Beam (LSB) has been introduced by Wahid Ferdous, Allan Manalo, Thiru Aravinthan and Amir Fam(Ferdous et al. 2018). Layered Sandwich Beam (LSB) is a sandwich system consisting of Phenolic cores and Glass Fiber Reinforced Polymer (GFRP) skins, and several layers of sandwich panels bonded together with an epoxy polymer matrix for manufacturing beams. In this study, shear and flexural behaviour of the LSB is investigated. In order to understand the behaviour of LSB, a numerical analysis was required and a finite element model was developed. The study demonstrates that LSB has improved sectional stability due to a reduction in wrinkling and buckling of composite skins as well as indentation failure. The study is done by Khalifa (Khalifa et al. 2017) to determine the quasi-static resistant function of new cost-effective lightweight cold-formed steel sandwich panels that could be used in blast-resistant structures. To predict elastic characteristics and to assess critical failure modes of this sandwich panel an analytical model is proposed. Also, eighteen sandwich panels were subjected to uniform quasi-static loads in this experimental program. Different deck profiles were used to investigate different sandwich configurations, including longitudinal and transverse corrugated core sandwich panels. Effect of sandwich panel core configuration and core sheet thickness on sandwich panel behaviour was investigated, taking into account energy absorption and ductility. Research on the flexural behaviour of prestressed composite beams with sandwich floor panels, rather than concrete slabs is done by Ryu (Ryu et al. 2020). In this study, the sandwich plate system (SPS) was used for floor panels. This SPS consists of two steel faceplates separated by a high-density polyurethane core. The flexural performance of prestressed SPS composite beams (PSCBs) was investigated. PSCB shows excellent ductile behaviour as well as a 14 % increment in the ultimate load-carrying capacity. Also, a finite element model capable of predicting the flexural behaviour of PSCB is proposed. The flexural analysis is done by Łukasz Smakosz, Ireneusz Kreja and Zbigniew Pozorski(Smakosz et al. 2020) on a composite structural insulated panel (CSIP) with magnesium oxide board facings and expanded polystyrene (EPS) core. A nonlinear FE model was created to stimulate the flexure behaviour of this composite. Also, lab experiments were done on this composite to verify the proposed model. A good correlation between the proposed model and the experimental result was observed.

In this paper, a simple empirical formula/analytical expression is proposed to calculate the buckling capacity of the sandwich panel. Column buckling theory is considered and applied to the steel aluminium foam sandwich panel to evaluate its behaviour under in-plane compressive load. Various assumptions are made to generalise Euler's buckling formula. The modified analytical expression is verified with finite element simulation employing various material models specific to steel face-plates and aluminium foam as well as various geometric imperfections.

2. IMPLEMENTATION OF BUCKLING FORMULA TO SANDWICH PANEL

Euler's buckling formula was applied to calculate the buckling capacity of the sandwich panel. For the sandwich panel, some assumptions were made as follows:

- Load is applied only on face-plates, not on the core;
- Core does not contribute to the buckling capacity (load carrying capacity) of the sandwich panel;
- Core has isotropic behaviour;
- Density of the core is homogeneous;
- During the manufacturing process proper metallurgical bond is established between the core and face-plates.

These assumptions allow Equation 1 to be used in order to calculate the sandwich panel's moment of inertia.

$$I = b(t^3 - t_c^3)/12 \quad (1)$$

The core is made from a material with a really small modulus of elasticity as compared to face-plate. Therefore, its contribution to buckling stiffness is ignored. The following procedure can be followed to calculate the buckling capacity of the sandwich panel.

Using Equation 2, the buckling stiffness of the sandwich will be:

$$EI = E_f b(t^3 - t_c^3)/12 \quad (2)$$

As shown in Equation 3, the Euler elastic critical buckling load can be described as:

$$N_{cr} = \pi^2 EI/L^2 \quad (3)$$

From this, the slenderness of the sandwich can be calculated as (Equation 4),

$$\lambda = \sqrt{A f_y / N_{cr}} \tag{4}$$

where,

$$A = 2bt_f \tag{5}$$

$$t = t_c + 2t_f \tag{6}$$

Therefore, the reduction factor is given by (Equation 7),

$$\chi = 1/(\phi + \sqrt{\phi^2 - \lambda^2}) \tag{7}$$

where,

$$\phi = 0.5[1 + \alpha(\lambda - 0.2) + \lambda^2] \tag{8}$$

Therefore, as per column buckling theory, the resistance of the sandwich panel can be given by (Equation 9),

$$N_{bRd} = \chi A f_y \tag{9}$$

3. FEA MODEL

In this study, for FEA, the same assumptions are considered as in section 2.

3.1 Considered model

A full-scale three-dimensional model was considered based on the dimensions as shown in the Figure 3.

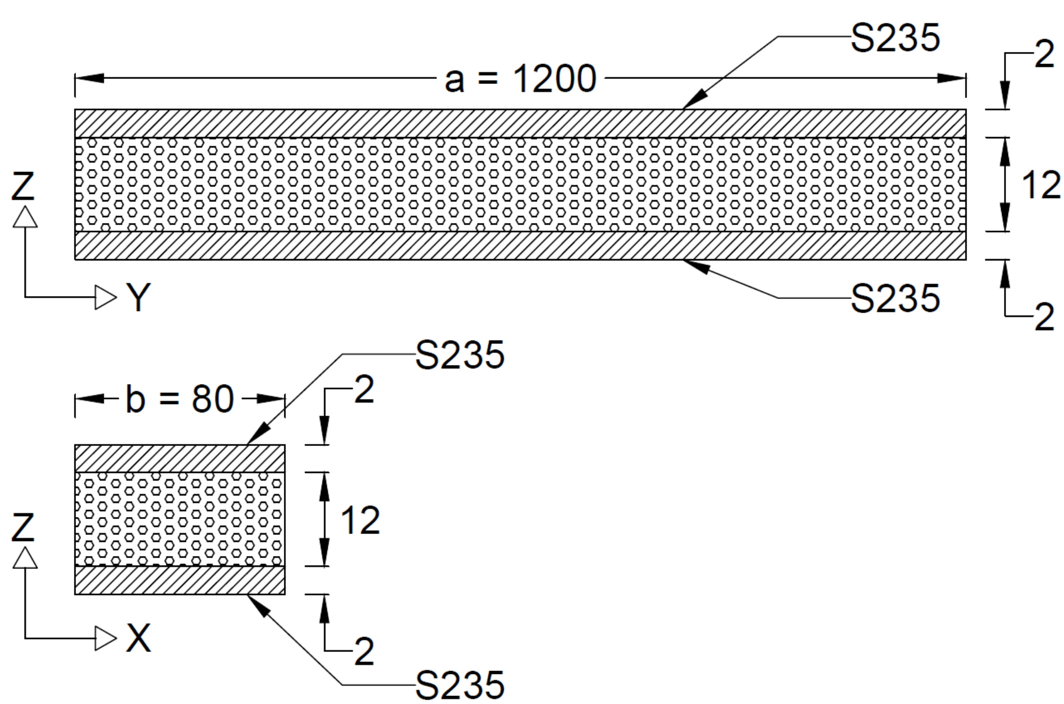


Fig. 3. Dimension of sandwich panel specimen (mm) (reproduced based on ref. S.S. Metal (2018)) (Havel metal foam GmbH 2018)

In Figure 3, 'a' is the length and 'b' is the width of the sandwich panel. The dimensions of sandwich panels are 1200 mm in length, 80 mm in width with a total thickness of 16 mm. This thickness is composed of 2 mm thick face-plates and 12 mm thick core. The face-plates are made of steel with a yield strength of 235 MPa, a modulus of elasticity of 210 GPa, a Poisson's ratio of 0.3, and a density of 7850 kg/m^3. The core is made of aluminium foam with a yield strength of 5 MPa, modulus of elasticity of 500 MPa, Poisson's ratio of 0.3 and density of 700 kg/m^3. The boundary conditions of the sandwich panel are illustrated in Figure 4. The bottom edge of the sandwich panel is constrained from all degrees of freedom except for rotation around the x-axis. At the top edge rotation around the x-axis and displacement along the y-axis is free and all other degrees of freedom are constrained. There are no constraints on the side edges of the sandwich panel. These boundary conditions are applied to stimulate the column behaviour of the sandwich panel.

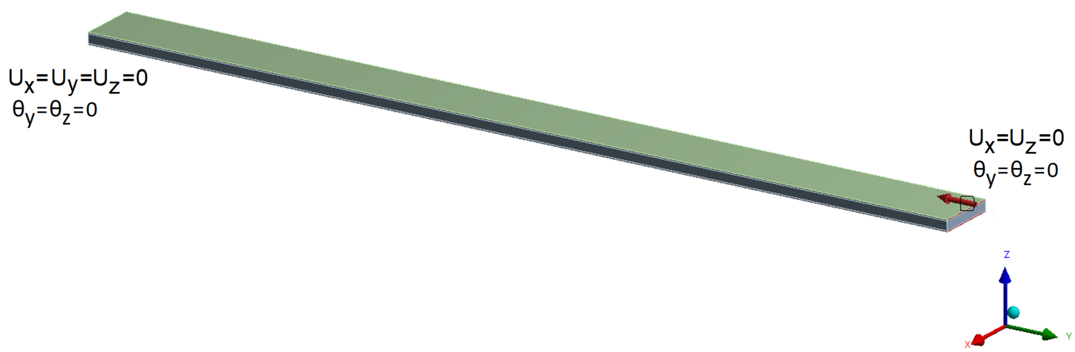


Fig. 4. Loading and boundary conditions of sandwich panel

In Figure 4, 'U_x', 'U_y', 'U_z' are displacements along x, y and z directions, respectively and 'θ_x', 'θ_y', 'θ_z' are the rotations around x, y and z directions, respectively.

The sandwich plane is loaded with in-plane compression along the y-axis and the displacement-controlled analysis is done. The displacement is applied only on face-plate since the contribution of the core to buckling is assumed negligible. The displacement that creates in-plane compression is applied in small increments. The reaction force corresponding to each increment is observed and it's possible to conclude that with an increase in the applied displacement, the corresponding force reaction increases and at a specific point the value of the force reaction drops (decreases). The force reaction corresponding to this point is considered as a load-carrying capacity of the sandwich panel. The Figure 4 shows the applied displacement on the sandwich panel.

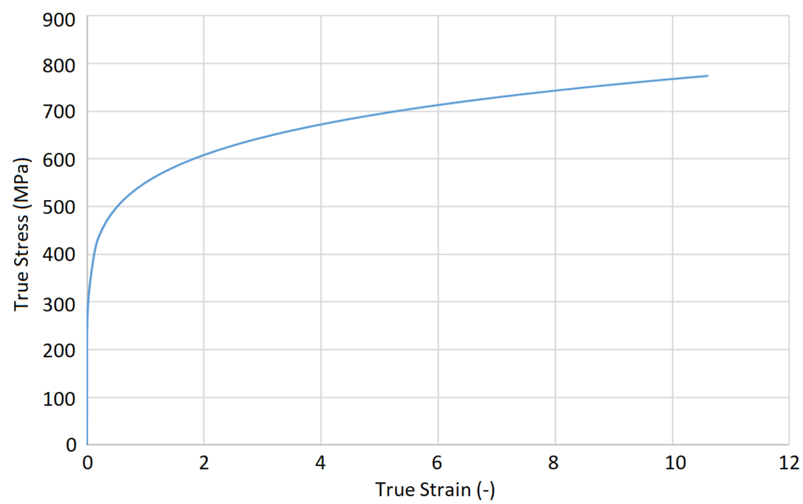
For modelling in ANSYS, SOLID186 element type is used. SOLID186 is a second-order 3-D 20-node solid element that exhibits quadratic displacement behaviour and it has 20 nodes having three degrees of freedom per node (x, y and z-direction). SOLID186 is an element which offers the ability to model local bending effects and because of its quadratic element property, it prevents hourglassing and shear locking.

In this study, three elements are used in the through-thickness direction to prevent hour-glassing(Peter 1994).

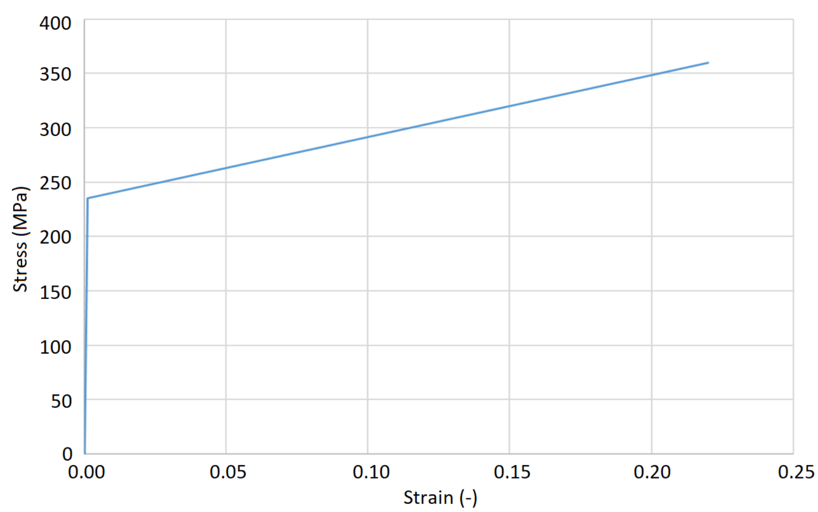
To verify the modified analytical expression, a finite element simulation employing various material models specific to steel face-plates and aluminium foam as well as various geometric imperfections was done.

3.2 Material models

The mechanical properties of the material can be illustrated with the help of stress-strain curves. In this study, the bi-linear model of steel, the multi-linear model of steel and the bi-linear model of aluminium foam are considered. Eurocode 1993-1-5(Beg et al. 2012) gives four different material models for the FE model. For the finite element analysis, the true stress-strain curve and bi-linear material model used for steel are illustrated in Figure 5a and Figure 5b. In the case of aluminium foam, only a few material properties are known. Therefore, only the bi-linear material model of foam with no strain hardening is considered. The material model used for aluminium is shown in Figure 6.



(a) Steel material model multi-linear



(b) Steel material model bi-linear

Fig. 5. Steel material models

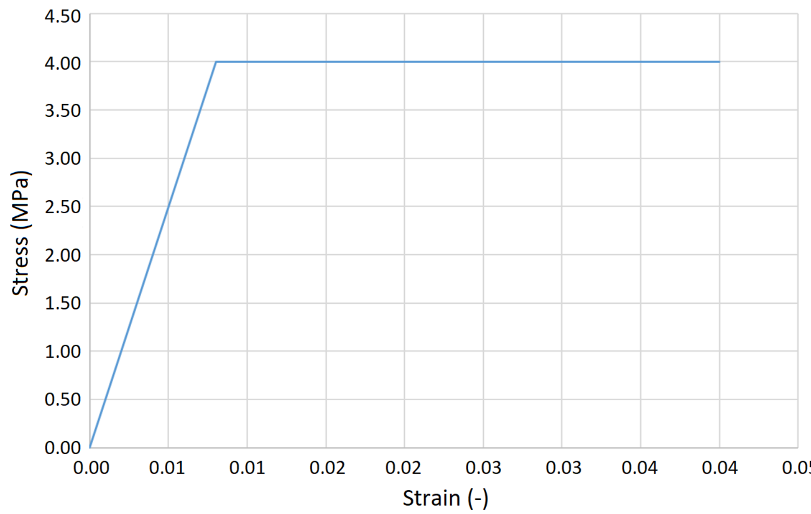


Fig. 6. Aluminium material model bi-linear

3.3 Geometric imperfections

Geometric imperfections can be global and local. The adopted non-linearity analysis approach incorporates both imperfections, curved geometry of panel in the global sense as well as imperfections on the local level. When the imperfection effect exists, the total stress is a result of stress due to axial load and bending. The strength of the steel member is always sensitive to imperfection in the shape of its Eigen-modes. Buckling modes of the structure taken from an Eigen buckling analysis can be used as elementary imperfection shapes. In ANSYS, initial deformation shapes can be easily imposed in the shape of Eigen buckling modes with a user-defined magnitude.

In this case, four different models with different values of imperfections are considered. Table 1 shows different values of the imperfections imposed on the structure. Figure 7 represents an idea of the structure with an imposed global geometric imperfection.

Model	Imperfection	Value of Imperfection(Global)
a	L/300	4
b	L/250	4.8
c	L/200	6
d	L/150	8
∗ *L* represents the length of the member		

TABLE 1. Design values of global geometric imperfection (Eurocode 2005)

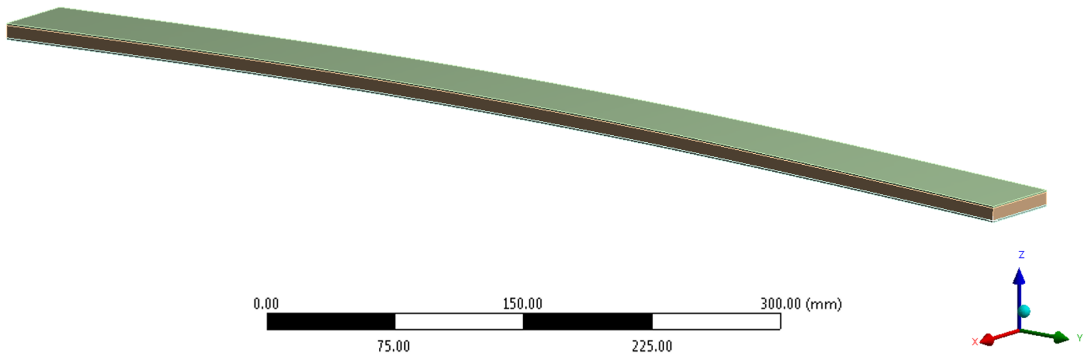


Fig. 7. Global geometric imperfection

Along with global imperfection, local imperfections can also exist in the structure. Table 2 shows the values of imperfection imposed on the structure.

Type	Imperfection	Value of Imperfection
Local	Min(a/200,b/200)	0.4
∗ *a* represents the length of the member		
∗ *b* represents the width of the member		

TABLE 2. Design value of local geometric imperfection (Eurocode 2005)

Figure 8 displays structure with local geometric imperfection,

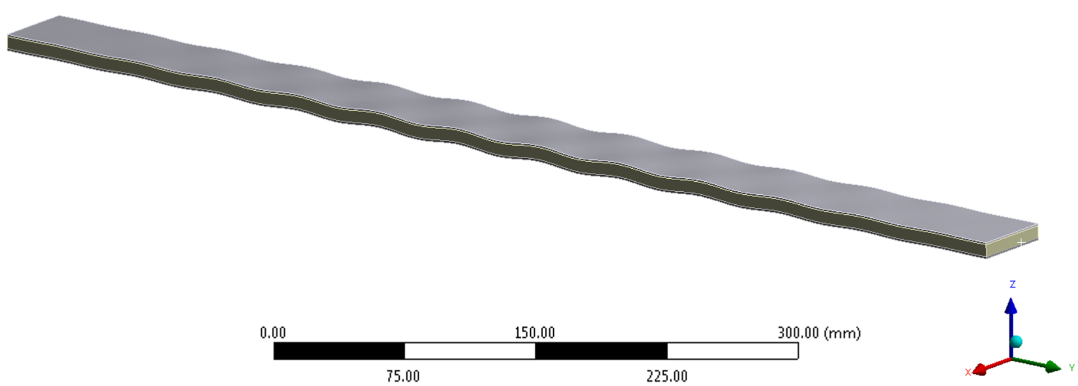


Fig. 8. Local geometric imperfection

4. FEA ANALYSIS

A finite element analysis considering geometric imperfections and material non-linearity (models) is used to determine the resistance of sandwich panel under pure compression. Eigen buckling analysis is done to get critical buckling load and buckling shapes. These buckling shapes will be used as initial imperfections in nonlinear analysis and the first fifty buckling shapes/modes are evaluated and plotted in the analysis.

As it is stated before that, imperfections in the shape of buckling modes are critical. Mode 1 is the first Eigen buckling mode, which results in the global buckling of sandwich panel with 1 half sine. Mode 42 shows the global buckling of sandwich panel with 42 half-sines. Until mode 43, sandwich panel was showing global buckling with the respective number of half sines. However, at mode 43 instead of buckling in 43 half sines sandwich started buckling on a local scale i.e., local buckling of face-plates is observed. Therefore, mode 43 is the first mode, which gives local buckling or local imperfections in a sandwich panel and these local imperfections observed in the face-plate are continuous or uniform. Thus, mode 1 is the first critical buckling mode which gives global buckling whereas mode 43 is the first critical buckling mode which gives local buckling and for that reason 1^{st} buckling mode and 43^{rd} buckling mode were used to impose global and local imperfections, respectively.

4.1 Global geometric imperfection

Buckling analysis is done on a sandwich with global geometric imperfection and various material models. These models are:

- Global geometric imperfections;
- Global geometric imperfections with steel bi-linear & aluminium linear;
- Global geometric imperfections with steel bi-linear & aluminium bi-linear;
- Global geometric imperfections with steel multi-linear & aluminium linear;
- Global geometric imperfections with steel multi-linear & aluminium bi-linear;

Table 3 shows the loads that can be applied when global geometric imperfections are considered along with various material models. The load values were calculated with the help of finite element analysis.

Load corresponding to first Eigen buckling mode (kN)	Geometric Imperfection Model	Load (kN)			
		Various Material Models			
		Steel Bi-Linear and Aluminium Linear	Steel Bi-Linear and Aluminium Bi-Linear	Steel Multi-Linear and Aluminium Linear	Steel Multi-Linear and Aluminium Bi-Linear
20.9	a	9.8	9.8	10	10
	b	9.5	9.5	9.8	9.8
	c	9.3	9.3	9.6	9.6
	d	8.9	8.9	9.2	9.2

TABLE 3. Result of FE Analysis on a sandwich with global geometric imperfection and material models

To find the resistance of the sandwich panel a non-linear analysis of the sandwich panel is performed. In this non-linear analysis, an applied displacement and its resultant force was calculated. The displacement was applied in short increments until the point where it is not possible to achieve force convergence and the model fails. The displacement increment and force reaction corresponding to it is arranged in a tabular form. The maximum force reaction can be treated as the load-carrying capacity of the sandwich panel. In addition, to visualise this, the graph between displacement increment and corresponding force reaction is plotted as shown in Figure 10 and Figure 11,

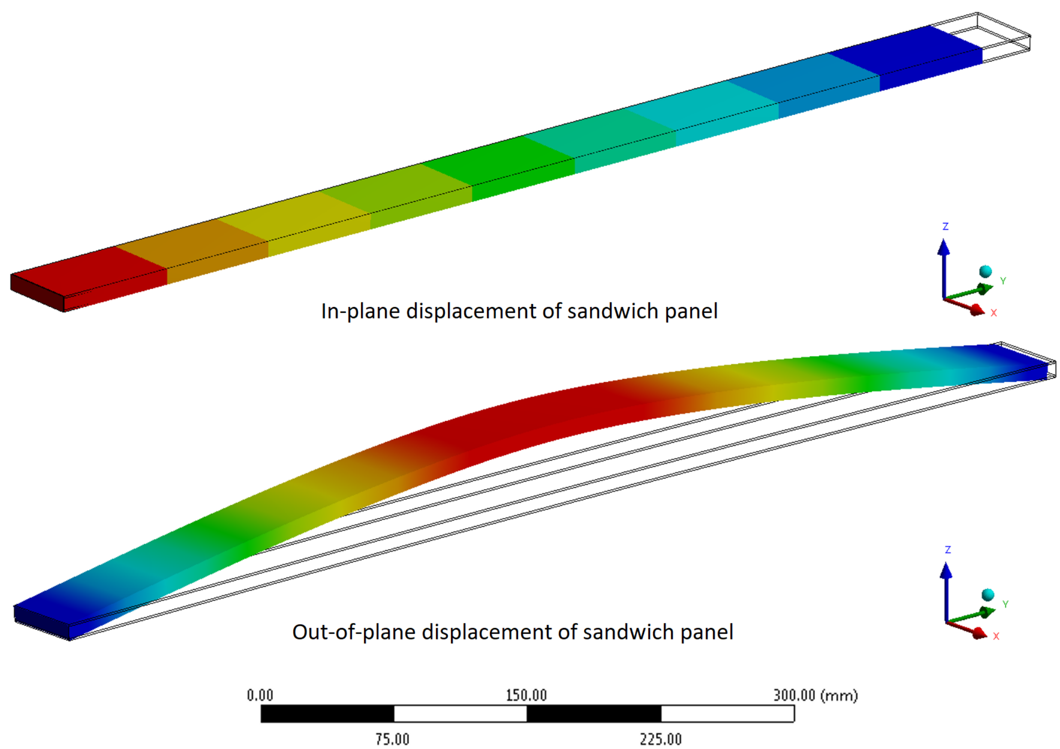


Fig. 9. Displacement of sandwich panel

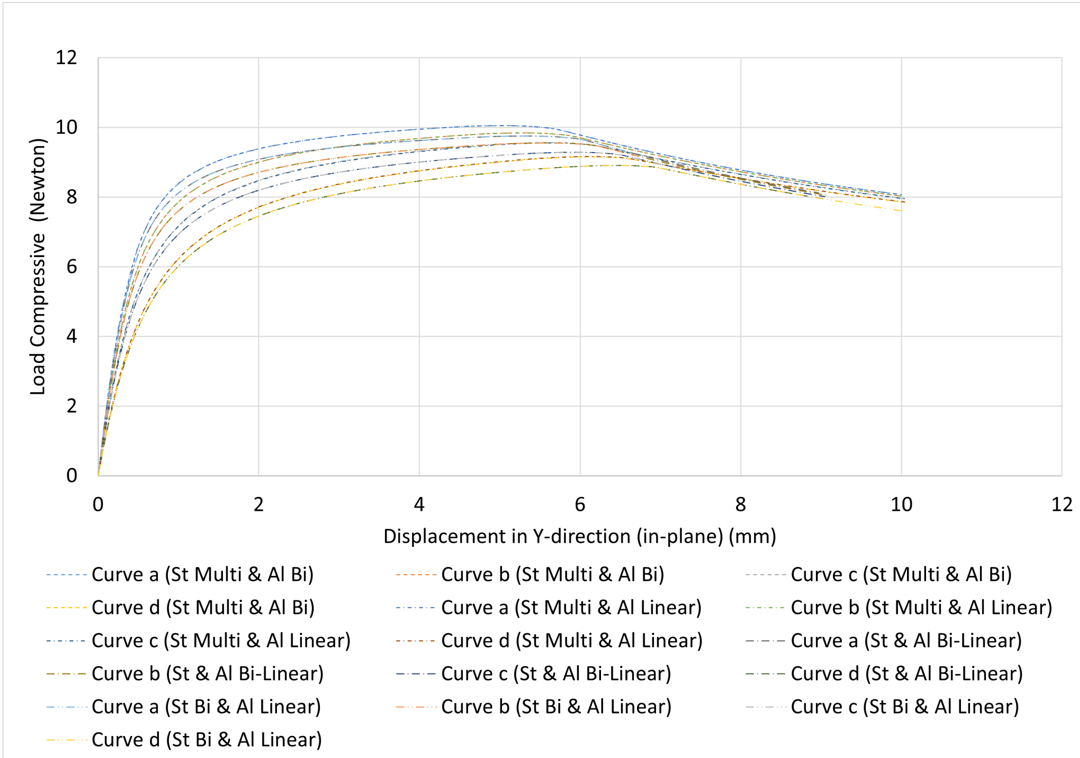


Fig. 10. Graph between in-plane displacement vs compressive load (global imperfection)

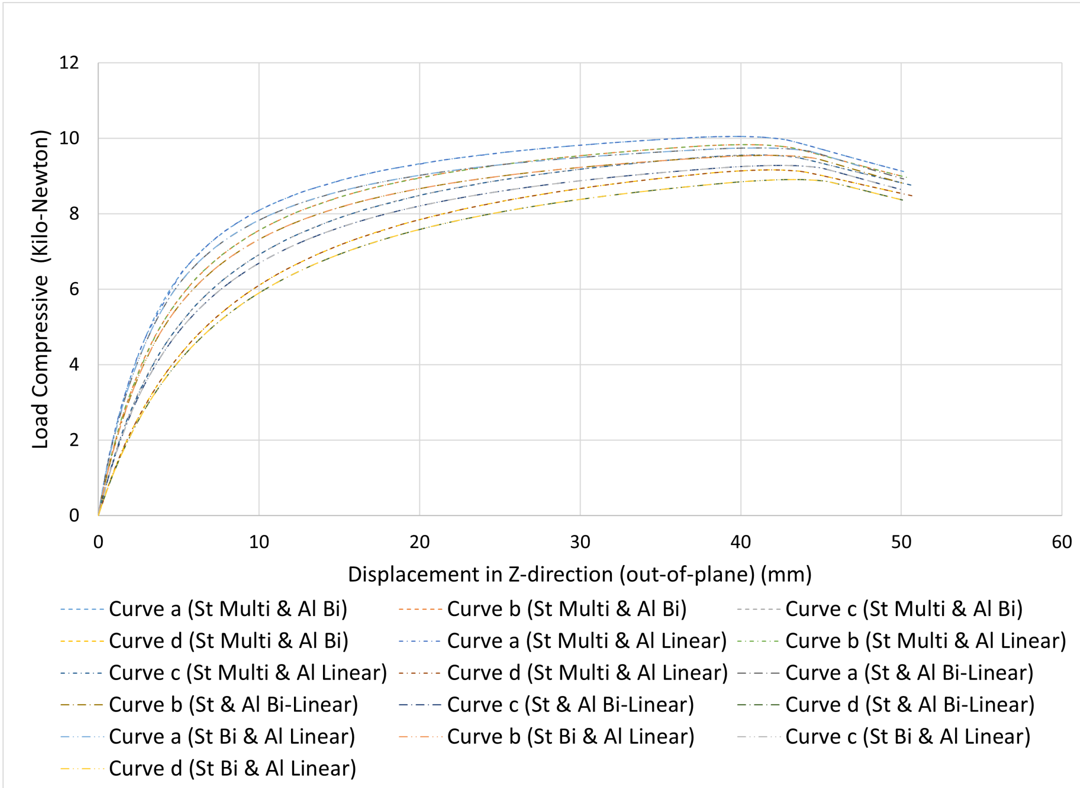


Fig. 11. Graph between out-of-plane displacement vs compressive load (global imperfection)

4.2 Local geometric imperfection

Buckling analysis is done on a sandwich with local geometric imperfection and various material models. These models are:

- Local geometric imperfections;
- Local geometric imperfections with steel bi-linear & aluminium linear;
- Local geometric imperfections with steel bi-linear & aluminium bi-linear;
- Local geometric imperfections with steel multi-linear & aluminium linear;
- Local geometric imperfections with steel multi-linear & aluminium bi-linear;

Table 4 shows the loads that can be applied when local geometric imperfections are considered along with various material models. The load values were calculated with the help of finite element analysis.

Load (kN)			
Local Geometric Imperfections with Steel Bi-Linear and Aluminium Linear	Local Geometric Imperfections with Steel Bi-Linear and Aluminium Bi-Linear	Local Geometric Imperfections with Steel Multi-Linear and Aluminium Linear	Local Geometric Imperfections with Steel Multi-Linear and Aluminium Bi-Linear
80	45	109	44

TABLE 4. Result of FE Analysis on a sandwich with local geometric imperfection and material models

In addition, to visualise this, the graph between displacement increment and corresponding force reaction can be plotted as shown in Figure 12.

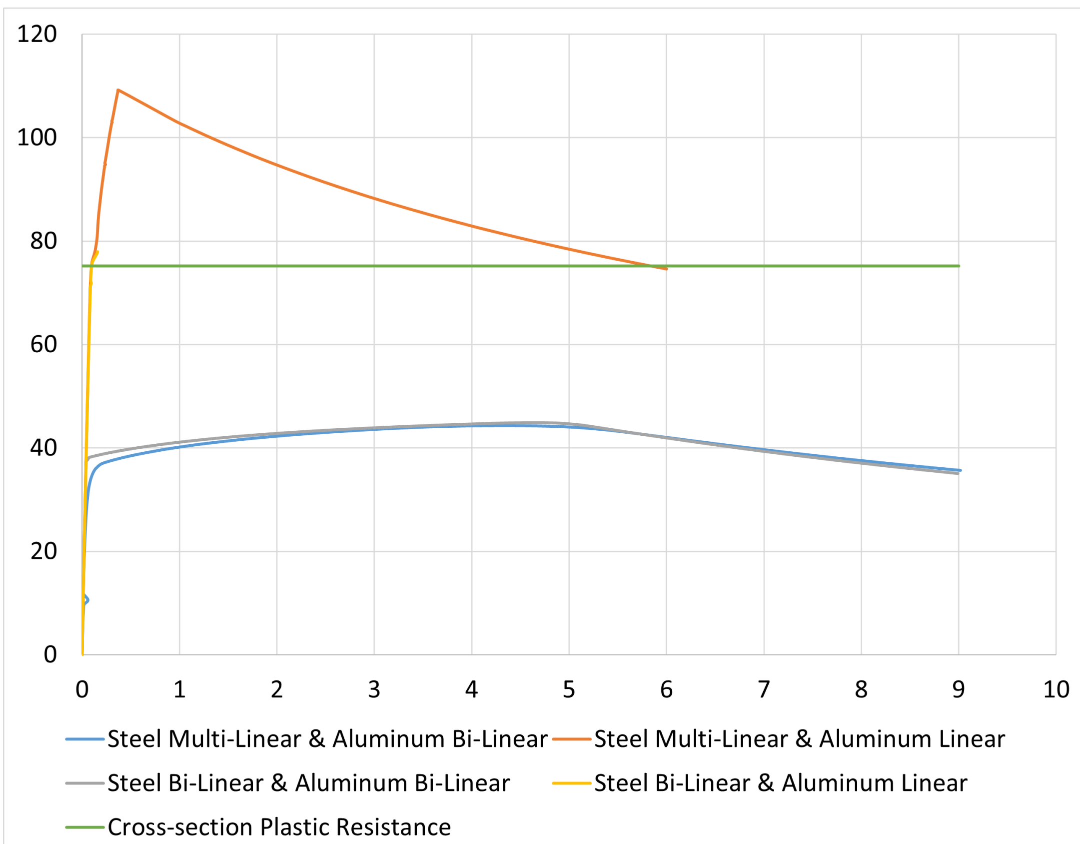


Fig. 12. Graph between out-of-plane displacement vs compressive load (local imperfection)

4.3 Combined local & global imperfection

In the above cases, global and local imperfections are considered separately but in practice, global and local imperfections can occur simultaneously in structure. This might result in an additional reduction in the load-carrying capacity of the structure. This value of load can be calculated analytically with the Equation 10,

$$F/F_{buck,global} + F/F_{buck,local} \leq 1 \tag{10}$$

According to Equation 10, the load-carrying capacity of a sandwich panel with both local and global imperfections is calculated and arranged in Table 5:

Load corresponding to first Eigen buckling mode (kN)	Geometric Imperfection Model	Load (kN)			
		Various Material Models			
		Steel Bi-Linear and Aluminium Linear	Steel Bi-Linear and Aluminium Bi-Linear	Steel Multi-Linear and Aluminium Linear	Steel Multi-Linear and Aluminium Bi-Linear
20.9	a	8.7	8.0	9.2	8.2
	b	8.5	7.9	9.0	8.1
	c	8.3	7.7	8.8	7.9
	d	8.0	7.4	8.5	7.6

TABLE 5. Result of FE Analysis on a sandwich with global and local geometric imperfection and material models

5. COMPARISON OF BUCKLING LOADS

A reduction factor can be used to compare the value of Eigen buckling load with load at buckling calculated with help of FEA. The reduction factor will illustrate a reduction in Eigen buckling load due to the presence of various geometric imperfections and considered material models.

5.1 Global imperfections

Geometric Imperfection Model	Reduction in Buckling Load			
	Various Material Models			
	Steel Bi-Linear and Aluminium Linear	Steel Bi-Linear and Aluminium Bi-Linear	Steel Multi-Linear and Aluminium Linear	Steel Multi-Linear and Aluminium Bi-Linear
a	0.47	0.47	0.48	0.48
b	0.46	0.46	0.47	0.47
c	0.44	0.44	0.46	0.46
d	0.43	0.43	0.44	0.44

TABLE 6. Reduction in buckling load for considered global geometric imperfection and material models

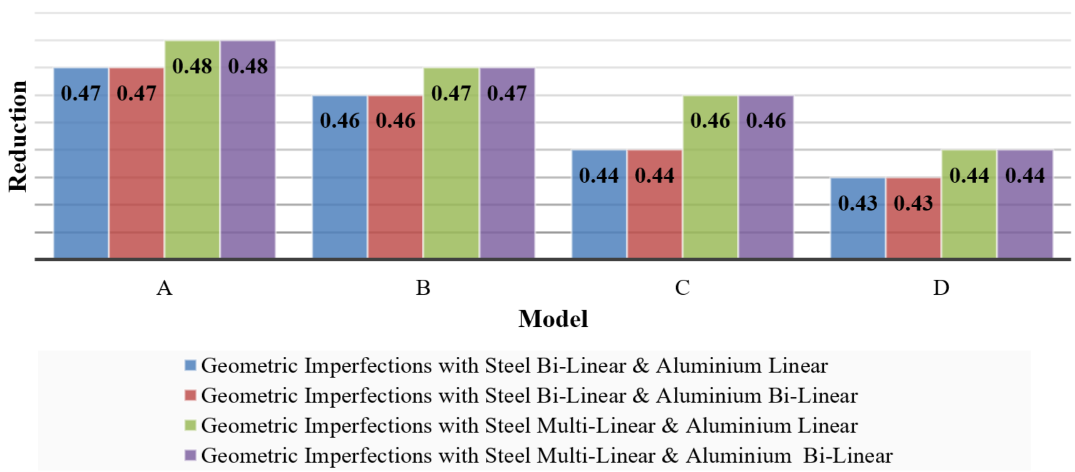


Fig. 13. Graphical representation of reduction in buckling load for considered global geometric imperfection and material models

From Table 6, it can be observed that in the case of the global imperfection, the material model used for face-plates affects the buckling capacity of the sandwich panel. On the other hand, the material model used for the core has a negligible impact on the buckling capacity of the sandwich panel. This might be due to the fact that on a global scale contribution of the core to the buckling capacity of the sandwich panel is negligible. This also validates the assumption, made for calculating the buckling capacity of a sandwich panel, that the core does not contribute to the buckling strength of the sandwich panel.

5.2 Combined local & global imperfection

Geometric Imperfection Model	Reduction in Buckling Load			
	Various Material Models			
	Steel Bi-Linear and Aluminium Linear	Steel Bi-Linear and Aluminium Bi-Linear	Steel Multi-Linear and Aluminium Linear	Steel Multi-Linear and Aluminium Bi-Linear
a	0.41	0.38	0.44	0.39
b	0.41	0.38	0.43	0.39
c	0.40	0.37	0.42	0.38
d	0.38	0.36	0.40	0.36

TABLE 7. Reduction in buckling load for considered global and local geometric imperfection and material models

From Table 7, it can be observed that in the case of combined global and local imperfection, the material model used for face-plates and core affects the buckling strength of the sandwich panel. This can be explained with help of the formula proposed by Howard Allen(Allen 2013). According to this, the critical stress for face wrinkling is largely dependent on the modulus of elasticity of the core. The formula proposed by Howard Allen(Allen 2013) is as follows,

$$\sigma_{cr} = B_1 E_f^{1/3} E_c^{2/3} \tag{11}$$

Where, B1 is a constant base on Poisson's ratio of the core.

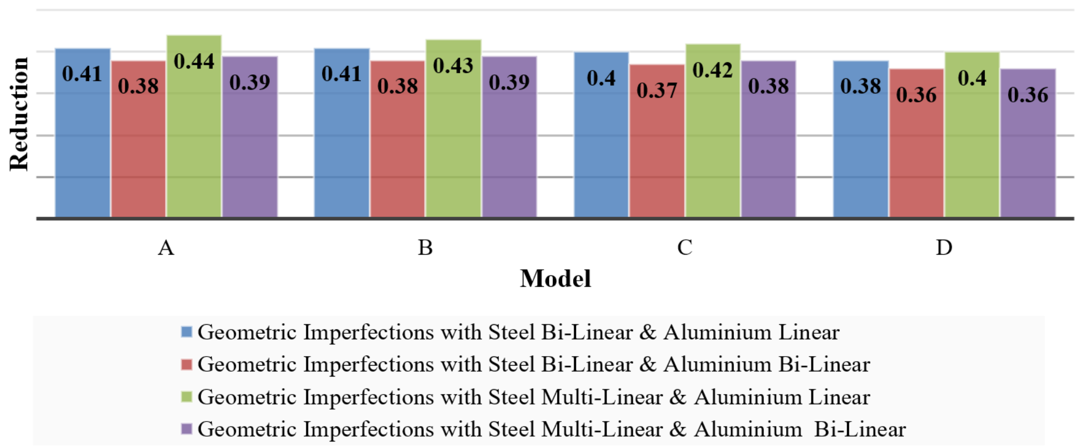


Fig. 14. Graphical representation of reduction in buckling load for considered global and local geometric imperfection and material models

6. CONCLUSION

This study is focused on the generalisation and modification of Euler's buckling formula, such that it can be applied to sandwich beams. It also focuses on the verification of this formula with the help of finite element analysis. Based on this study, it can be concluded that Euler's buckling formula can be successfully modified and used in the prediction of the load-carrying capacity of a sandwich panel.

In presence of geometric imperfections, material models used for face-plates have a significant impact on load-carrying capacity, whereas material models of core have a very small or negligible impact on the load-carrying capacity of a sandwich panel. This is because, on a global scale, the core has no contribution to the buckling resistance of the sandwich panel. This also justifies the theory, which states that the contribution of the core to buckling stiffness is negligible. As per the theory, the stiffness of the sandwich panel can be calculated using Equation 12,

$$EI = E_f b(t^3 - t_c^3)/12 \tag{12}$$

From this equation, it can be observed that the stiffness of the panel is dependent on the modulus of elasticity of the face-plate. This can explain why the material model used for face-plate has a considerable impact on the load-carrying capacity of a sandwich panel with global imperfection.

In the presence of local imperfections, material models used for both face-plate and core greatly affect the load-carrying capacity of a sandwich panel. As per Howard Allen(Allen 2013), stress for face wrinkling can be calculated by Equation 13 ,

$$\sigma_{cr} = B_1 E_f^{1/3} E_c^{2/3} \tag{13}$$

Where, B1 is a constant base on the poison's ratio of the core.

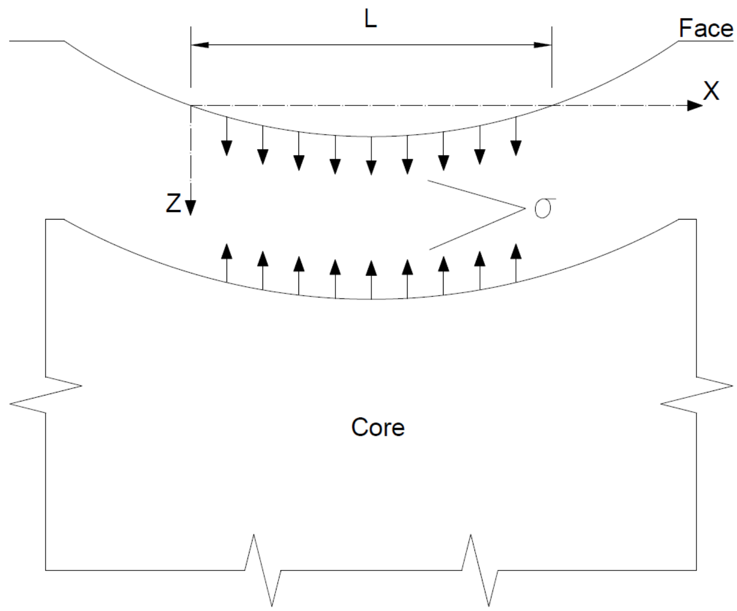


Fig. 15. Stress between the face-plate and supporting elastic medium (core)

From this equation, it can be observed that critical stress is largely dependent on the modulus of elasticity of the core. This can explain why the material model used for the core has a considerable impact on the load-carrying capacity of a sandwich panel with local imperfection.

It is encouraged to continue an investigation for sandwich panels in steel constructions to keep on pushing limitations. The lab test should be done on the sandwich panel so as to justify this proposed theory. Also, compression and buckling tests should be done on a sandwich panel and numerical and experimental data should be compared. This will also help in understanding the real-life behaviour of sandwich panels under in-plane compression and flexural buckling. More research should be done to establish some rule like the Eurocode, which can be referred to during designing a structure with sandwich panels.

ACKNOWLEDGMENTS

This study was supported by the Delft University of Technology and Huisman Equipment. Also, thanks to Ben van de Geer, Alexander Richter & Havel Metal Foams for providing all the information related to the sandwich panel which was required for this study as well as giving me an opportunity to visit their production facility which was an enriching experience.

REFERENCES, CITATIONS AND BIBLIOGRAPHIC ENTRIES

APPENDIX I. NOTATION

The following symbols are used in this paper:

- A = total area of both face-plates of the sandwich panel (mm^2);
- B_1 = constant based on Poisson's ration of core;
- b = width of the sandwich panel (mm);
- EI = buckling stiffness of the sandwich panel ($N - mm^2$);
- E_{c} = modulus of elasticity of the core of the sandwich panel (MPa);
- E_{f} = modulus of elasticity of the face-plate of the sandwich panel (MPa);
- F = load-carrying capacity of a sandwich with both local & global imperfections (kN);
- $F_{\mathrm{buck,global}}$ = load-carrying capacity of a sandwich panel with global imperfections (kN);
- $F_{\mathrm{buck,local}}$ = load-carrying capacity of a sandwich panel with local imperfections (kN);
- f_{y} = yield strength of face-plates of the sandwich panel (MPa);
- I = moment of inertia of the sandwich panel (mm^4);
- L = length of the sandwich panel (mm);
- N_{bRd} = buckling resistance of the sandwich panel (MPa);
- N_{cr} = Euler elastic critical buckling load of the sandwich panel (N);
- t = total thickness of the sandwich panel (mm);
- t_{c} = thickness of core of the sandwich panel (mm);
- t_{f} = thickness of face-plate of the sandwich panel (mm);
- U_{x} = displacement along x direction (mm);
- U_{y} = displacement along y direction (mm);
- U_{z} = displacement along z direction (mm);
- θ_{x} = rotation along x direction;
- θ_{y} = rotation along y direction;
- θ_{z} = rotation along z direction;
- σ_{cr} = critical stress for face wrinkling of the sandwich panel (MPa);
- α = imperfection factor;
- λ = non-dimensional slenderness of the sandwich panel;
- ϕ = constant to determine the reduction factor χ; and
- χ = reduction factor.

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Replies to reviewers comments

Reviewer #1: The paper aims to investigate the column buckling theory to steel aluminium foam sandwich panels in the context of a lightweight design. Various assumptions are made to generalize Euler's buckling formula. The generalization requires modification of the buckling stiffness expression to account for sandwich panel composite properties. In general, the paper is well-presented. The topic is quite innovative. Both theoretical and numerical sections are clear. The results can justify the publication of the research. Therefore, the manuscript can be accepted for publication in the current form, since the topic falls within the aim of the journal.
Answer: The authors are grateful to the reviewer for the positive comments on our manuscript.

Reviewer #2: Please consider the comments added to the pdf attached file. If possible, I added some questions regarding the work that was done and that could enlight more the document.

- What type of local geometric imperfections was adopted in the non-linearity analysis ? Are they only related to the material?

Answer:
In the case of nonlinearity, both material and geometric nonlinearity is considered. Local geometric imperfections that were adopted are explained in sub-section 3.3 and their values are shown in table 2.

- How was the sandwich panel geometry chosen? Why were these considerations taken? Any specific case of study to be adressed?

Answer:
An experiment has been performed on the sandwich panel at the University of Surrey in collaboration with Havel metal foam. The geometry considered in this study is a result of that experiment which cannot be mentioned here due to classified industrial documentation.

- Why wasn't a different type of bending mode studied?

Answer:
The presented work aims to redesign an existing structure with the help of sandwich panels. The dominating failure mode for the structure is flexural buckling. Therefore, only the buckling of the sandwich panel is studied which was required by the company.

- A chapter regarding future works and solutions to mitigate global/local imperfections could be added regarding the results of this work.

Answer:
The aim and focus of the presented work were to understand the behaviour of sandwich panels under in-plane compression and buckling. Also, to find out the simple way to derive the buckling capacity of the sandwich panel which can be used or referred to while working with the sandwich panel.

But the study about mitigating the global and local imperfections of sandwich panels will be related to the manufacturing process of sandwich panels. An in-depth study can be done on the manufacturing process of sandwich panels and achieving a perfect sandwich with minimum imperfections. But this study will be related to the field of metallurgy. Therefore, it doesn’t fit the scope of the current study.

As future works
- Testing the modified Euler's buckling formula with experimental data to validate its accuracy in predicting the load-carrying capacity of the sandwich panel instead of using only the numerical simulation.

Answer:
It is encouraged to continue an investigation for sandwich panels in steel constructions to keep on pushing limitations. The lab test should be done on the sandwich panel to justify this proposed theory. Also, compression and buckling tests should be done on a sandwich panel and numerical and experimental data should be compared. This will also help in understanding the real-life behavior of sandwich panels under in-plane compression and flexural buckling. More research should be done to establish some rule like the Eurocode, which can be referred to during designing a structure with sandwich panels.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: