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Educational Software for Stress Analysis of Open Thin-Walled Structures

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ABSTRACT

Thin-walled structures are commonly employed in aerospace and automotive structures because of their high strength to weight ratio. Design and hence the stress analysis of thin-walled structures is tedious and time-consuming. An educational software which can aid students in stress analysis of thin-walled open sections will enhance the teaching-learning process. With the present available software, the number of sections that can be analysed is limited, hence in this work, a generalized section has been developed through which many new complex sections can be generated and analysed for stresses. The objective of the present work is to develop educational software that will provide a solution for the section properties like centroid, moment of inertia and shear centre, and the stresses on the section for a given loading. The software enables students to select different cross-sections which may be subjected to bending, shear or torsional loads and evaluate the stresses on it. Results obtained through this software have been validated against literature. The software has been developed using MATLAB with graphical user interface (GUI). The software is expected to be a useful tool for effective teaching learning process of courses on thin-walled structures, aircraft structures and advanced mechanics of materials.

1. Introduction

Modern aviation constructions, or more precisely, their supporting structures are made almost exclusively as thin-walled structures that perfectly fulfill the postulate to minimize the weight of the construction [1]. It can be said that thin-walled structures are the perfect solution for constructing an aircraft with least weight. The weight is a very important solution in aircraft design since it will have an impact on the flight performance and economic efficiency. Aerospace structures such as fuselage and wings are made of typical thin-walled sections and the detailed stress analysis of such thin-walled structures is tedious and time consuming. Hence for the students who learn aerospace structures, an educational software for stress analysis of thin-walled structures will act as a complementary tool to traditional teaching and learning methods. Using this software, the students can repeat and research a variety of problems in a short time and gain confidence in the subject, thus achieving the outcomes of the course. With the software as a step-by-step guidance in hand, the

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students can check their mistakes and correct themselves. This will save the student's time as well as that of the lecturers. Furthermore, lecturers can use this software for framing short term projects. The importance and role of educational software in engineering education is well brought out by Philpot [2] in his work on MDSolids, a software for Mechanics of Materials.

Educational Software can be defined as computer programs that can be used for teaching and learning purposes [3]. It can be categorized into two parts which are Content-free Software and Content-rich Software. Content-free Software offers a wide platform of teaching and learning activities while Content-rich Software is a built-in software that consists of specific objectives which are limited to particular subjects.

Joo-Nagata *et al.,* mentioned that the educational software is a computer software with the primary purpose of teaching or self-learning [4]. The educational software is anticipated to be a cutting-edge instrument that is accountable for enhancing the teaching-learning process for both lecturers and students and create a favorable learning environment. To provide an effective and efficient teaching-learning process in this technological era, it is crucial to update the teaching methodologies. Educational software can have a variety of types which are authoring system, graphics software, reference software, desktop publishing, tutorial software, educational games, simulations, drill and practice software, math problem solving software, utility software, and special needs software.

Technology has influenced the current education system in many aspects. Teachers or lecturers may improve their technology proficiency since the computer is able to further their goals, that is, reduce perceived costs and increase perceived benefits. One of the applications of the technologies that is widely used in education is educational software. There are many engineering educational software that are currently available. All types of engineering such as aerospace engineering, electrical engineering and others have their own educational software. Using the right educational software for every engineering subject can greatly enhance the student's understanding and retention [5].

One of the engineering educational software that has been developed is Electrical Engineering Educational Software which was created by Nani Fadzlina and her team [6]. This software was purposive to assist the lecturers and students in electrical engineering courses since it is capable of providing a visualization of the subjects from the plots, graphs, and images and execute the answer automatically. The software is basically based on MATLAB and a Graphical User Interface (GUI). However, the user can use the software without installing MATLAB on his or her Personal Computer (PC) since the software is designed as a standalone program. A good GUI consists of controls such as menus, toolbars, buttons, and sliders. Moreover, educational software that has been developed by MATLAB GUI does not require the user to learn a language or command in order to run the application. DYNASOFT is a web based educational package which helps in teaching structural dynamics [7]. Similarly, SECav is an educational software which supports the learning and teaching process of numerical calculus courses [8].

Educational software for stress analysis of open and closed thin-walled sections has been developed by Mohamed Ali and his team [9-12]. This educational software plays a role as a modern tool to greatly enhance the teaching-learning process on solving the stresses on thin-walled sections. The educational software for the stress analysis of open thin-walled structures was developed by Mohamed and Nurhuda [9] to enhance the teaching-learning process of course on Aircraft Structures. This software was developed based on the Visual Basic platform and it was used by the students to validate their solution while solving assignments/projects, thus saving a lot of time in completing the assignment. In addition, this software also benefits the lecturer in a way of easing the teaching and learning process as the students can solve problems independently with the software that gives step-by-step solutions and guides the student as a lecturer. But this software had a limitation in the types of sections it can handle as depicted in Figure 1.

Furthermore, educational software for stress analysis of non-idealized open section made of composite thin-walled sections has also been developed [13,14]. Basically, this educational software methodology is similar to the previously mentioned software except with the procedure corresponding to mechanics of composite material was used. The focus of that software was on the stress analysis of laminated composite thin-walled open sections only.

Based on the literature review, it can be concluded that the detailed stress analysis of complex thin-walled structures is tedious and time consuming and hence to motivate the students an educational software will be useful. Moreover, the available educational software only provides stress analysis limited for standard sections like I, T, C, L, and Z section [9] as shown in Figure 1, whereas typical thin-walled sections that are of complex shapes as shown in Figure 2 cannot be analyzed using that software. Hence, a self-study package or educational software that can perform stress analysis for any generalized section need to be developed so that students have freedom to generate any shape of the thin-walled section and carry out stress analysis of these thin-walled sections. The present work aims to develop such an educational software using MATLAB.

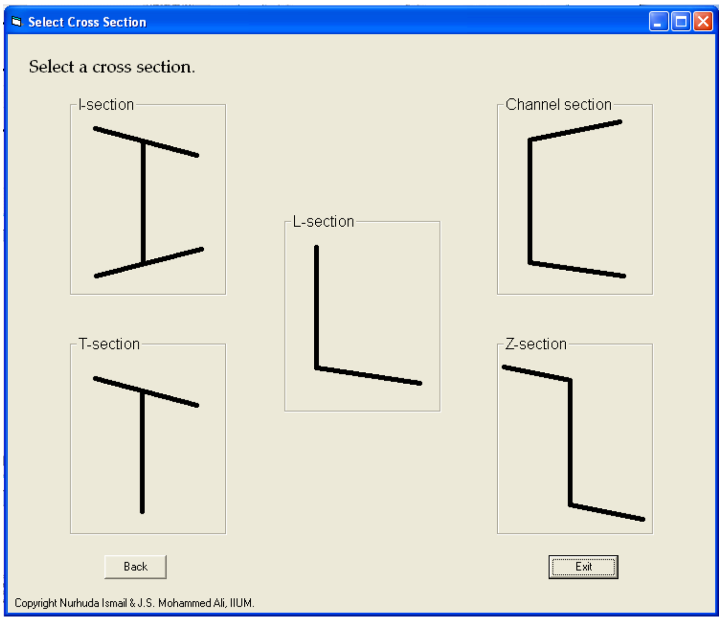

Fig. 1. Available section for stress analysis [9]

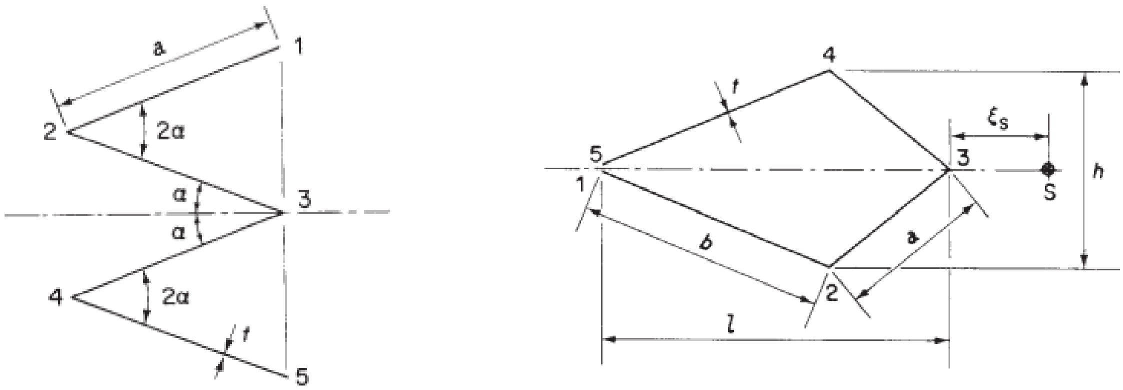

Fig. 2. Typical Complex sections (Megson [15])

2. Methodology
2.1 Theory of Stress Analysis of Thin-Walled Structures

An unsymmetric thin-walled open section subjected to bending moment (M_x and M_y) shear forces (S_x and S_y) and torsional moment (T) as shown in Figure 3 is considered for analysis. A thin-walled open section is made from an assembly of flat elements. A section is said to be thin-walled if its thickness is small compared to the cross-sectional dimension; the ratio of the thickness to the cross-sectional dimension being at least one tenth (1/10). As the theory for stress analysis of thin-walled open section is well established in the literature, the theory and methods of calculation have been adopted from Megson [15] except where it is stated otherwise.

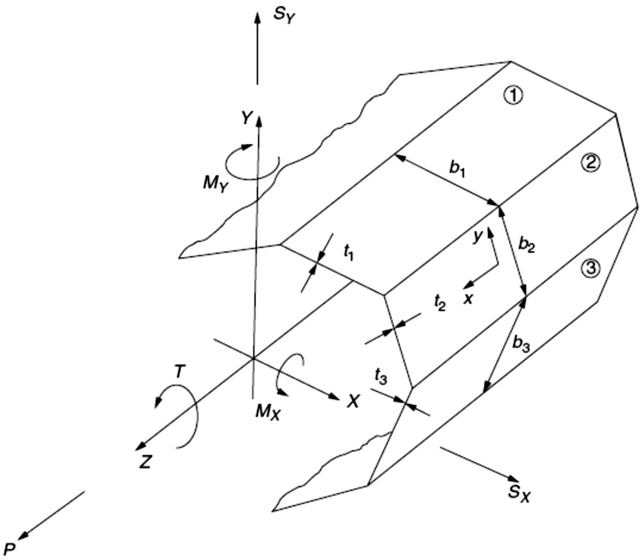

Fig. 3. Typical thin-walled section with loading

Firstly, the section properties of the thin-walled section need to be calculated which will used in the stress analysis of the thin walled structure. Section properties are the location of the centroid, location of the shear center, and the moments of inertia. Both vertical and horizontal location of the centroid and shear center need to be calculated. Calculation of these properties is straight forward for simple sections whereas for complex sections such as shown in Figure 2, it is tedious, and the students are bound to make mistakes.

2.1.1 Theory of bending

An applied load which causes a beam to bend produces direct stress which varies across the cross-section of the beam. The value of direct stress at a point in the cross-section depends on the position of the point, the applied loading and the geometric properties of the cross-section. It is of no effect whether the cross-section is open or closed. To find direct stress σ_z due to bending moments about the x-axis, M_x, and about the y-axis, M_y, shown in Figure 1, the following equation is used with I_{xx}, I_{yy} and I_{xy} are the moment of inertia:

$$\sigma_z = \left(\frac{M_y I_{xx} - M_x I_{xy}}{I_{xx} I_{yy} - {I_{xy}}^2}\right) x + \left(\frac{M_x I_{yy} - M_y I_{xy}}{I_{xx} I_{yy} - {I_{xy}}^2}\right) y \tag{1}$$

2.1.2 Flexural shear stresses

In bending of beams, the theory considering solid or thick beam sections can be extended to the thin-walled beam sections typical of aircraft structural components. However, for thin-walled beams subjected to shear, the theory is based on assumptions applicable only to thin-walled sections. Shear of an open section beam produces flexural shear stresses. However, it is more convenient to work in terms of shear flow q, i.e. shear force per unit length rather than in terms of shear stress τ. The equation for shear flow is:

$$q = \tau t \tag{2}$$

where q is regarded as being positive in the direction of increasing s (local coordinate) and t is the thickness. Figure 1 shows the thickness t, shear loads S_x and S_y applied on an open section beam.

There can be two cases of a section subjected to shear forces. First, the lines of action of the shear forces pass through the shear centre and the second, the lines of action of the shear forces do not pass through the shear centre. In the first case, there will be no twisting of the beam cross-section while in the second case there will be twisting of the cross section. Thus, the shear centre can be defined as a point on a cross-section through which shear loads produce no twisting.

When the shear loads are passing through the shear centre of a section, shear stress due to flexure alone will be produced in the section. To calculate the flexural shear flow, the following equation can be used [5]:

$$\int_0^s \frac{\partial q}{\partial s} ds = -\left(\frac{S_x I_{xx} - S_y I_{xy}}{I_{xx} I_{yy} - {I_{xy}}^2}\right) \int_0^s tx\ ds + \left(\frac{S_y I_{yy} - S_x I_{xy}}{I_{xx} I_{yy} - {I_{xy}}^2}\right) \int_0^s t\,yds \tag{3}$$

If the origin for s is taken at the open edge of the cross-section which makes q = 0 when s = 0, the equation above becomes:

$$q_s = -\left(\frac{S_x I_{xx} - S_y I_{xy}}{I_{xx} I_{yy} - {I_{xy}}^2}\right) \int_0^s tx\ ds + \left(\frac{S_y I_{yy} - S_x I_{xy}}{I_{xx} I_{yy} - {I_{xy}}^2}\right) \int_0^s t\,yds \tag{4}$$

For shear loads not passing through the shear centre, the loads can be separated into two parts. First, the shear force is shifted to the shear centre. Then, the moment of the shear force in its actual location about the shear centre is used as the applied torque. The net shear stress is obtained by superimposing the shear stresses due to pure flexure and pure torsion [16]. The flexural shear stress can be calculated using Eq. (4) followed by Eq. (2), while the calculation of torsional shear stress will be as discussed in the next section.

2.1.3 Shear centre

For a section with an axis of symmetry, the shear centre lies on this axis. For cruciform or angle sections, the shear centre is located at the intersection of the sides as the internal shear loads all pass through this point.

For other thin-walled open sections, the position of the shear centre (ξ_S, η_S) has to be calculated. To find ξ_S, an arbitrary shear load S_y is applied through the shear centre which results in a shear flow distribution in the cross-section as given by Eq. (4). The moment about any point on the cross-section produced by these shear flows is equivalent to the moment of the applied shear load about that same point. It is wise to choose a web/flange junction as a moment centre as it would reduce the amount of computation needed. The shear flows in the webs/flanges which do not pass through the moment centre should be integrated with respect to *s* (i.e.$\int_0^s q\, ds$) to obtain the internal shear forces. Then, the internal shear forces are multiplied by the respective perpendicular distances of their lines of action to the moment centre to obtain the internal moments. The position of the shear centre in the x-direction, ξ_S, can be found by equating the moments of the internal shears about the moment centre with the moment of the applied shear load S_y about the same point. Then, to find the position of the shear centre in the y-direction, η_S, a shear load S_x is applied through the shear centre. After that, η_S is determined in a method similar to the determination of ξ_S.

2.1.4 Torsion

Unlike the shear centre and shear flow procedure explained before the calculation of shear stresses due to torsion is straight forward, the torsion constant *J* is calculated using the following equation:

$$J = \sum \frac{bt^3}{3} \tag{5}$$

where *b* is the breadth of an element (web/flange) in the thin-walled section and *t* is its thickness. The torsional shear stress in an open section varies linearly from a positive value on one surface of the element to a negative value on the other surface. The maximum shear stress on an element can then be written as:

$$\tau_{max} = \pm \frac{tT}{J} \tag{6}$$

The rate of twist of the beam is:

$$\frac{d\theta}{dz} = \frac{T}{GJ} \tag{7}$$

where *G* is the shear modulus of the material.

2.2 MATLAB-Graphical User Interface (GUI)

MATLAB is a high-performance language which combines visualization, programming environment and computation. Compared to other computer languages like C and FORTRAN, MATLAB provides a powerful built-in program that can access any kind of computation [12]. Based on these findings, GUIDE (Graphical User Interface development environment) has been selected to develop this educational software. GUIDE provides a set of tools for creating graphical user interfaces (GUIs) which simplify the process of designing and building GUIs greatly [13]. GUI is a graphical display that illustrates the results graphically and computationally. MATLAB GUIDE is a user friendly language which makes it very easy for the user to learn and understand independently.

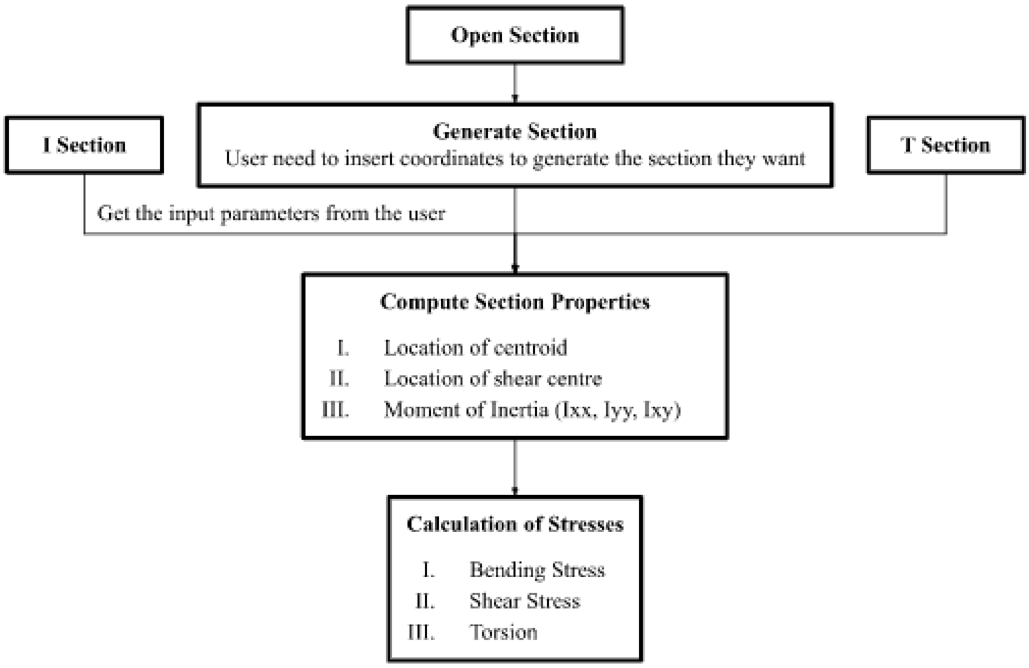

Fig. 4. Flow chart for the stress analysis

Basically, the equation for section properties and stresses needs to be generalized first before being implemented into the coding in MATLAB. Such that, the equation needs to be formulated according to the possible scenarios created by the user which includes symmetrical, unsymmetrical, and inclined section. As a next step, designing the layout of the GUI was done. Unlike in the other software [9] where there were standard shapes to pick up, here there is an option to generate section using which the user can construct his own section (Figure 5.). The user will then be asked to enter the number of coordinates, n (where n is the no the edges/corners) required to construct the generalized section (Figure 6). Then, the user is prompted to fill in the input like coordinates and thickness (Figure 7) which then displays the section with its properties and then the user can select the analysis they want to perform either bending, shear or torsion (Figure 8). Finally, the output of the desired stress will be displayed in tabular or graphical form. The flow chart of the stress analysis procedure that is followed by the software is depicted in Figure 4.

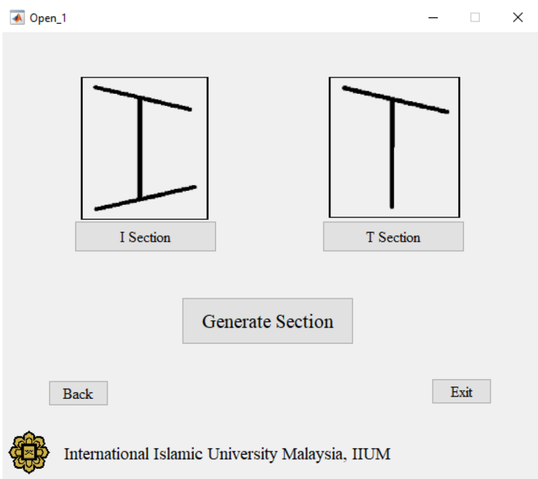

Fig. 5. GUI for selection of section

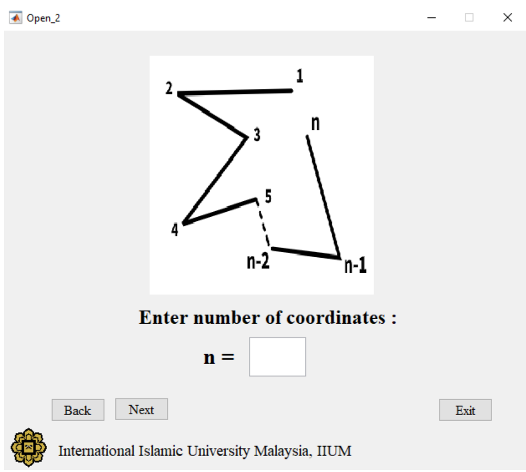

Fig. 6. GUI for number of coordiantes

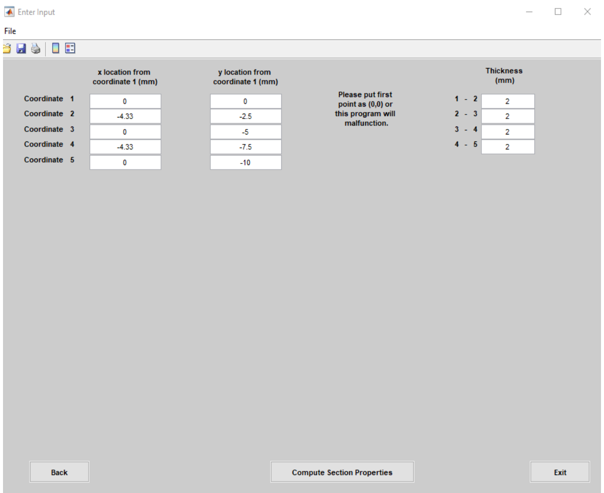

Fig. 7. Typical GUI Coordinate inputs

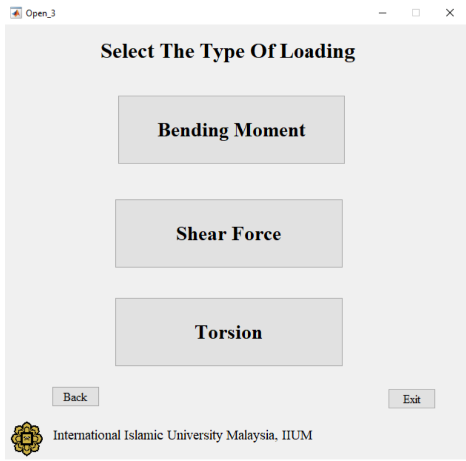

Fig. 8. Loading Selection GUI

3. Results and Discussion

To check the software, different case studies have been attempted and all the outputs from the software have been validated. Firstly, the section properties output from the software is validated and following that all the other three load cases are considered. To demonstrate the capability of the software first complex sections are selected from standard text book on Aircraft structures by Megson [15].

3.1 Case Study 1: Section Properties

A beam has the singly symmetrical, thin-walled cross-section shown in Figure 9. Each wall of the section is flat and has the same length, *a* and thickness, *t*. The distance of the shear centre from the point 3 needs to be calculated.

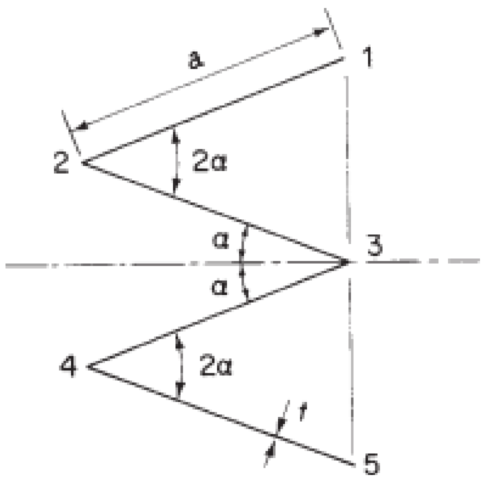

Fig. 9. Section properties case study [15]

Although the section considered here is symmetric, the section is complex in terms of its geometry with inclined sections and challenging in terms of location of shear centre. Table 1 indicates the value used for each variable in the case study. Basically, the construction of the generalized section needs to be done first. Firstly, the number of coordinates, n (which is the number of corners/edges) required to construct the section must be inserted like in Figure 10.

Table 1
Value used for the variables

Parameters	Value
α	30°
a	50 mm
t	2 mm

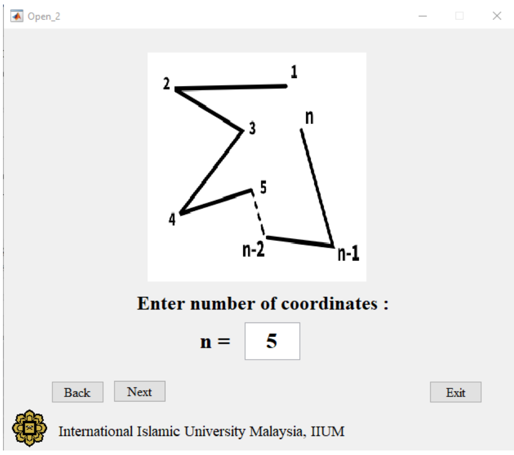

Fig. 10. No of corners input

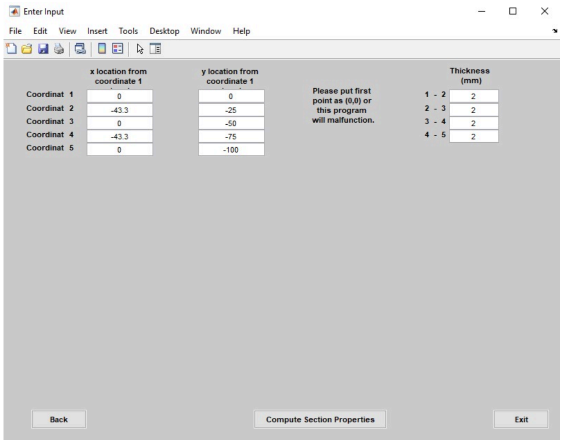

Fig. 11. Coordinates Input

Figure 11 is where the coordinates to construct the intended section are required to be filled in. Coordinate 1 needs to remain as (0,0). Coordinate 2 is where the user starts to construct the section. Taking the case study section, coordinate 2 needs to be on the left and bottom of coordinate 1. Hence, the value for x and y coordinates is taken to be negative. Then, the value for the remaining coordinates are entered with respect to coordinate 1. Then, the thickness of each element in the provided box needs to be given. The "Compute Section Properties" key must be pressed in order to view the Centroid, Shear Centre and Moment of Inertia as shown in Figure 12.

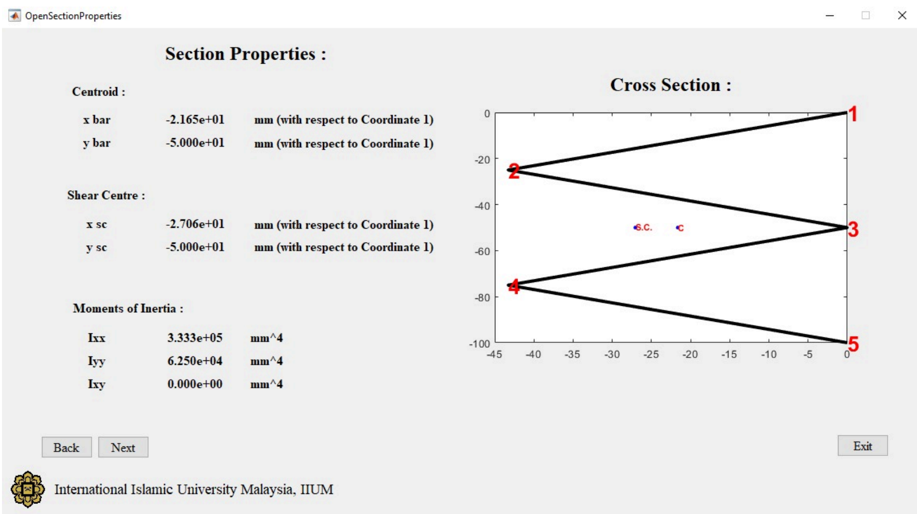

Fig. 12. Section properties window

Basically, any generalized section can be generated using the same method mentioned above. Stress analysis of the generated section can be done by clicking the "Next" button in the section properties window like in Figure 12.

Eq. (8) and Eq. (9) are the solution for this problem given in the textbook. Only the final equations are presented here, to obtain these equations one may need to work at least 30 to 45 mins long. The variables need to be substituted with the value in Table 1 to obtain the I_{xx} and horizontal location of the shear center of the section.

$$I_{xx} = \frac{16a^3 t sin^2\alpha}{3} \tag{8}$$

$$\xi_s = \frac{5a\cos\alpha}{8} \tag{9}$$

Based on the results presented in Table 3, it can be observed that the software executed the exact section properties like the solution from textbook. Hence, it can be said that this software is functioning effectively on calculating the section properties for the generalized section.

Table 3
Validation of Section properties

Section Properties	Result from software	Result from Megson [15]
I_{xx}	$3.333 \times 10^5\ mm^4$	$3.333 \times 10^5\ mm^4$
ξ_s	$-27.06\ mm$	$-27.06\ mm$

3.2 Case Study 2: Bending Stress

Next, bending stress of the generalized section is examined, for which a unsymmetric section is selected for to illustrate the capability of the software in evaluating bending stress. The thin-walled beam section shown in Figure 13 is subjected to a bending moment M_x. The maximum direct stress in the section needs to be determined. Taking a = 100 mm, t = 1 mm and M_x = 25000 N-mm.

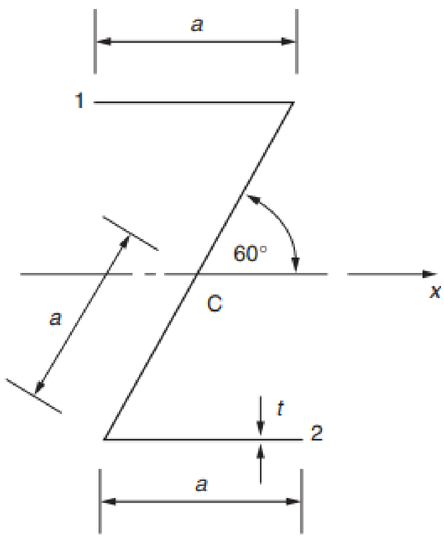

Fig. 13. Bending stress case study [15]

Figures 7 and 8 indicate the construction of the generalized section for the bending stress case study. It is similar to that what was described before using n = 4 for to generate this section (Figure 6) which lead to input window of coordinates (Figure14) and the output gives the section properties (Figure 15).

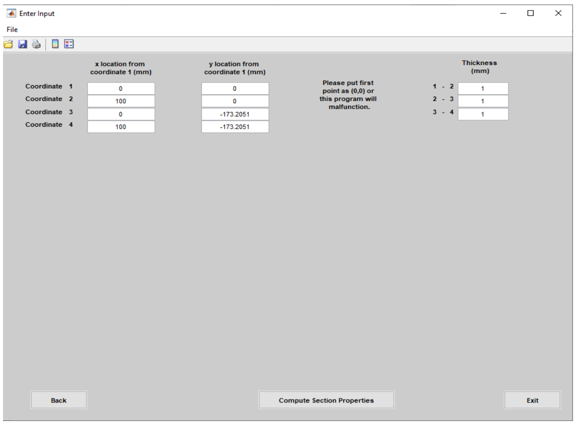

Fig. 14. Coordinate Inputs and thickness

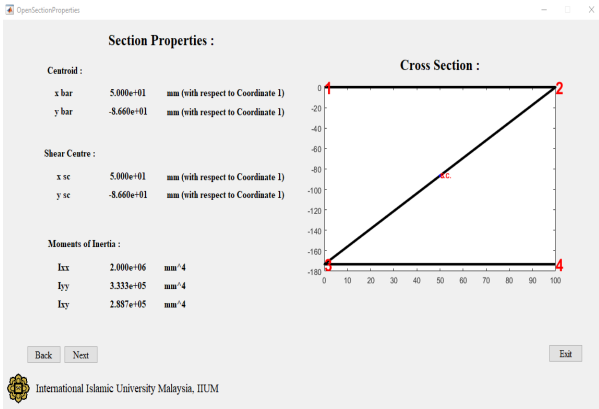

Fig. 15. Section Properties of the section

Figures 16 and 17 shows the bending stress result and 3-D stress plot executed by the software respectively. Since the case study asks to find the maximum direct stress, the stress at point 1 and point 4 needs to be determined as the greatest stress will occur at points furthest from the neutral axis. However, the solution given by the textbook is only for point 1, hence the location that needs to be entered in the software is (0,0) which indicates the location of point 1.

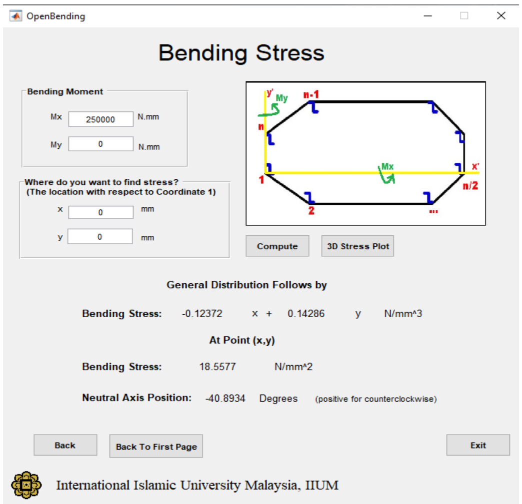

Fig. 16. Bending stress Input

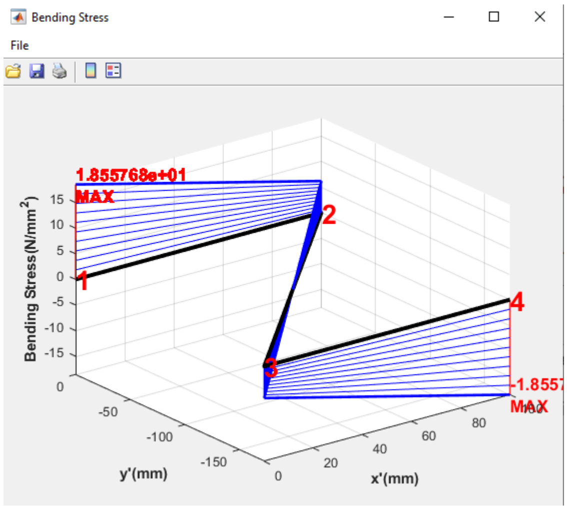

Fig. 17. Stress Distribution

Eq. (10) gives the final solution given by the textbook [15] for the bending stress case study.

$$\sigma_{z,max} = \frac{0.74M_x}{ta^2} \tag{10}$$

Following the results that have been obtained from both software and textbook solution (Table 4), it can be said that the software is able to predict exactly the bending stresses for any generalized section.

Table 4
Validation for Bending Stress

Location	Result from software (N/mm^2)	Result from Megson [15] (N/mm^2)
Point 1	18.5577	18.5

3.3 Case Study 3: Flexural Shear Stress

Figure 18 shows the singly symmetrical cross-section of a thin-walled open section beam of constant wall thickness t, which has a narrow longitudinal slit at the corner 15. The distribution of shear flow due to a vertical shear force S_y acting through the shear centre, S need to be found.

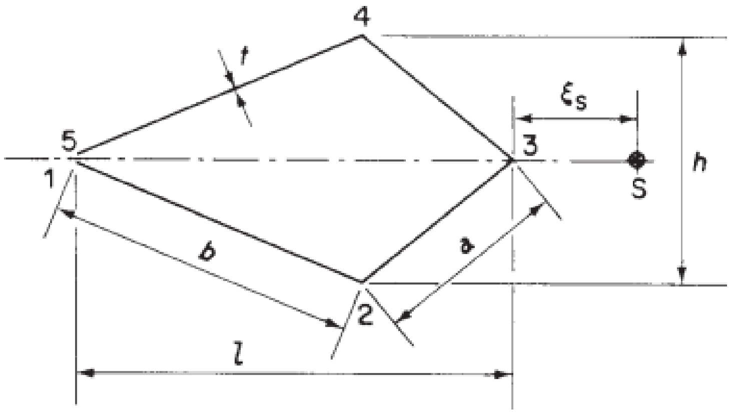

Fig. 18. Shear stress case study [15]

Table 2 gives the value used for each variable in the shear stress case study with S_y = 350 N.

Table 2
Value used for the variables

Parameters	Value (mm)
a	100
b	200
h	120
l	270.8
t	1.5

Figure 19 is the input window of coordinate inputs for the construction of the generalized section and Figure 20 gives the computed section properties for the shear stress case study problem.

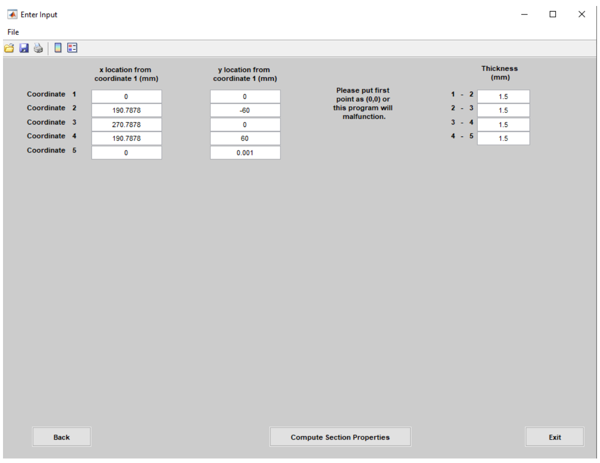

Fig. 19. Coordinates and thickness

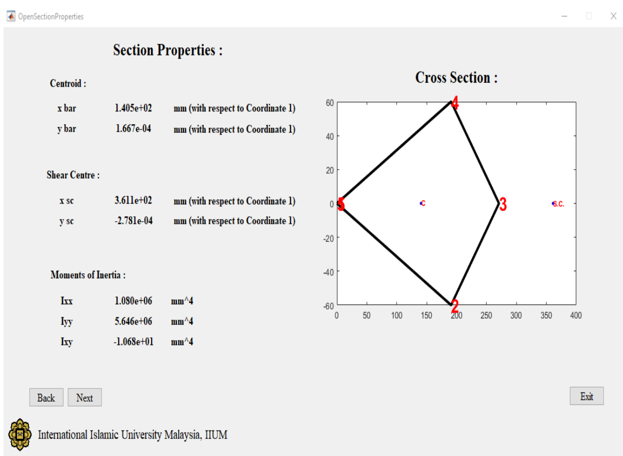

Fig. 20. Computed section properties

Figure 21 illustrates the shear force input and the cross section that the user wants to examine for shear stress. After the user completely fill in the parameters, the shear flow and shear stress will be presented in the next window (Figure 22). Note that the value to be given is 0 for s1, s2, s3, and s4 since the purpose of this analysis is to find the shear flow at point 2, point 3 and point 4.

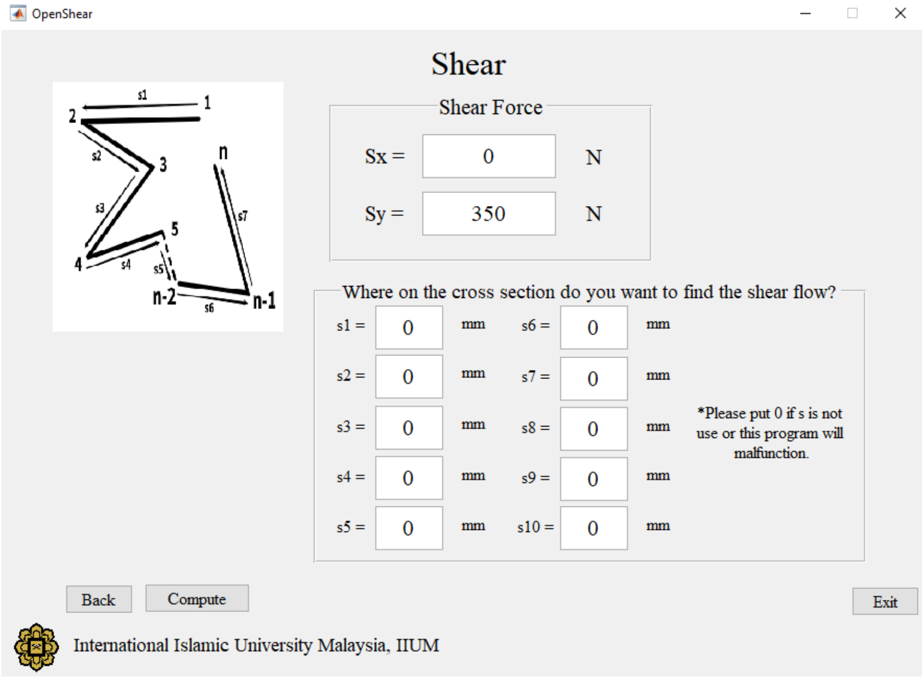

Fig. 21. Shear force input

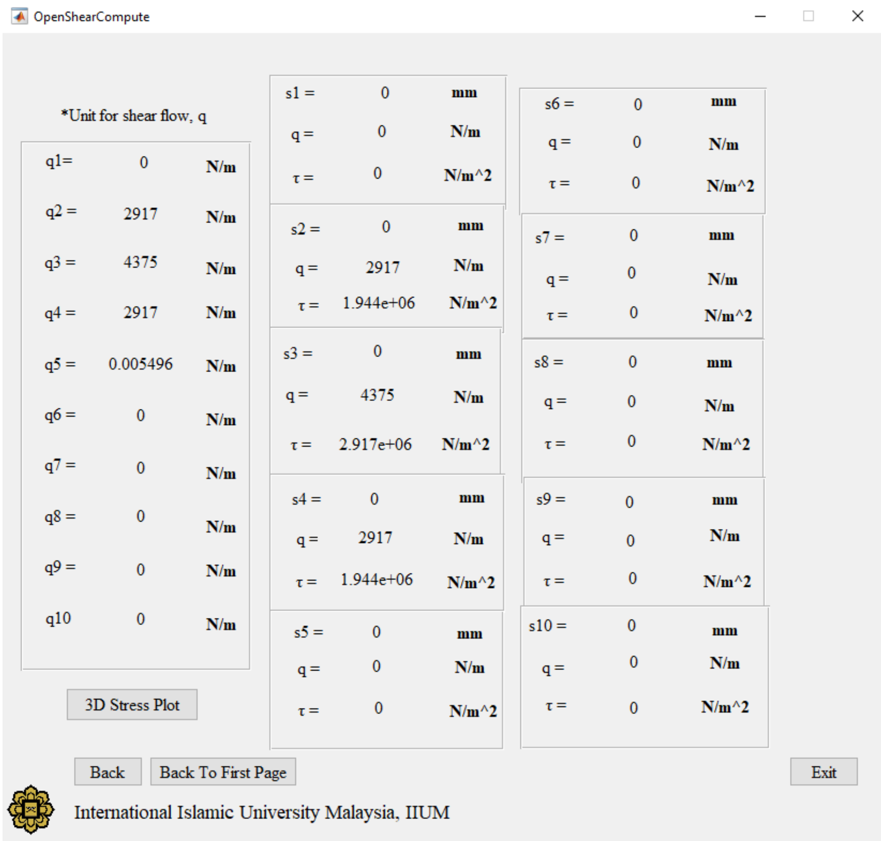

Fig. 22. Shear stress result from the software

Eq. (11) and Eq. (12) are the final equation of solution that is given by the textbook. The variables in the equation need to be substituted with the value in Table 2 to attain the shear stress results as shown in Table 5.

$$q_2 = q_4 = \frac{3S_y b}{2h(b+a)} \tag{11}$$

$$q_3 = \frac{3S_y}{2h} \tag{12}$$

Based on the results presented in Table 5, it can be concluded that this software is capable of determining the shear stress for any generalized section. As point 1 and 5 are open edges it has $q_1 = q_5 = 0$.

Table 5
Validation of Shear Stress

Cross Section	Result from software (N/m^2)	Result from Megson [15] (N/m^2)
q_2	2917	2917
q_3	4375	4375
q_4	2917	2917

3.4 Case Study 4: Torsion

Despite the torsional shear stresses analysis is straight forward, it has been added for the sake of completeness. The cold-formed section shown in Figure 23 is subjected to a torque of 50 N m. Hence, the maximum shear stress in the section and its rate of twist needs to be calculated. Take G = 25 000 N/mm^2.

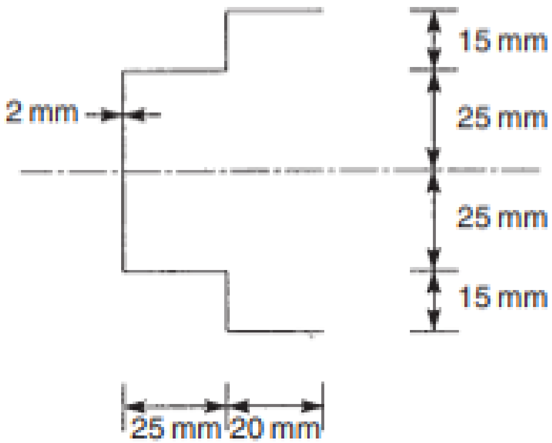

Fig. 23. Torsion case study [15]

As in previous case studies, the input window was used for the coordinate inputs for the construction of the generalized section and then section properties were computed.

Figure 24 is the user-interface where the applied Torque, T and shear modulus, G is required to be filled up by the user. The results of the maximum shear stress and angle of twist per unit length will be given as output in the following window (Figure 25).

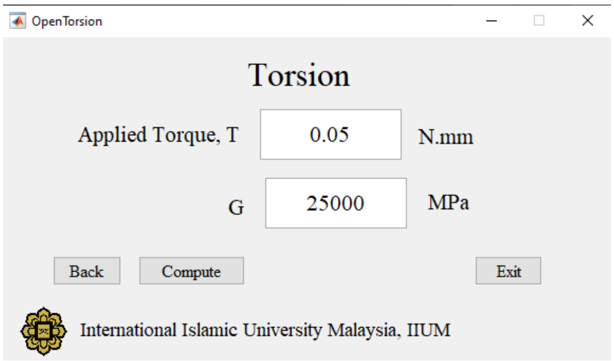

Fig. 24. Torque and Shear Modulus input

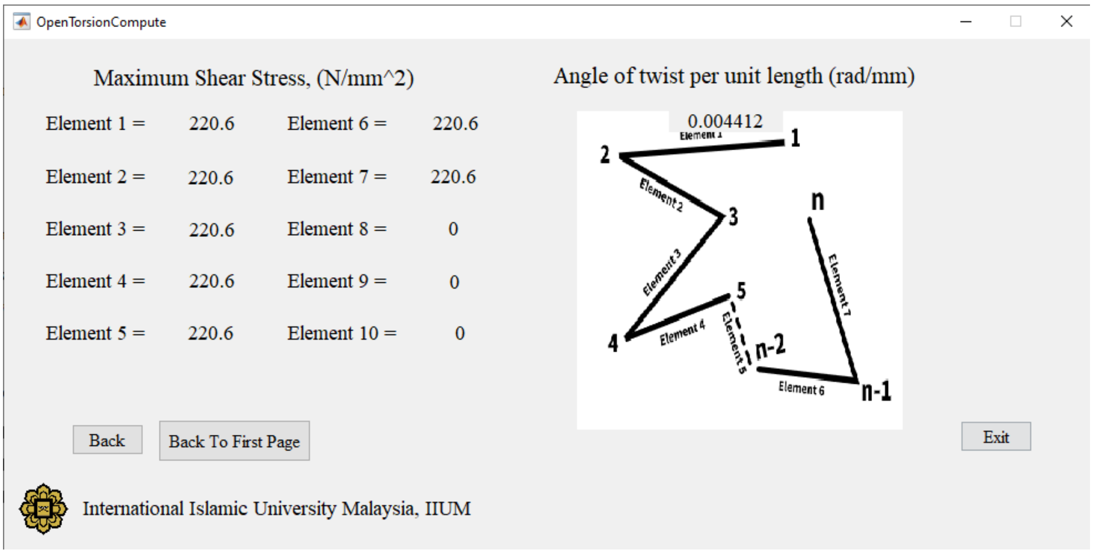

Fig. 25. Maximum shear stress and angle of twist per unit length result from the software

Following the results presented in Table 6, it can be noted that both the maximum shear stress and angle of twist per unit length are predicted accurately. Hence, it can be concluded that this software can calculate the bending stress, flexural shear stress, and torsional shear stresses with twist accurately.

Table 6
Validation of Torsional Shear Stress and Angle of twist per unit length

	Maximum Shear Stress N/mm^2	Angle of twist per unit length (rad/mm)
Megson [15]	220.6	0.0044
Software	220.6	0.004412

4. Conclusions

An educational software useful to perform stress analysis of thin-walled open sections has been developed. The software includes a generalized section which allows the user to construct any section they need to analyze either simple Z, T, L, C, or any other complex sections. The software has been developed using MATLAB, graphical user interface (GUI) which makes it user friendly. Extensive validation of the results has been done against available literature for all the loading cases with different complex sections and the results obtained were found to be in excellent agreement. It is intended that this software can be a useful educational tool for students, complementing textbooks and in-class lectures. This educational software is expected to raise the interest of the students in learning the related subject and empowering individuals with the knowledge and skills necessary to understand and analyze aircraft structures effectively.

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