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A System-of-Systems Inspired Framework to Enhance Aerospace Structural Mechanics Education

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Abstract

We initiated a System-of-Systems inspired framework (i.e., Definition, Abstraction, and Implementation) to enhance aerospace structural mechanics education. The proposed framework has a possibility to become an active learning pedagogy in mechanics education since the difficulty level may be adjusted for students to fit right in the Zone of Proximity Development. The framework can also promote healthy collaboration among the students as well as between students and instructors for critical thinking and engagement. The framework is a streamlined version of "the big picture to the small picture" approach, so the students can always see the big picture, which helps them to understand how everything fits together and fosters creativity. In the framework, we created specific examples of how structural mechanics educators can start using the approach immediately (i.e., a summary table and a two-table approach) to solve cross sectional properties (i.e., a centroid location, area moments of inertia, and product of inertia). Finally, as a future work, combining the System-of-Systems inspired framework with digital teaching techniques like virtual lab could be an exciting topic since the interactive and multimedia environment appeals to today's students who are comfortable using digital media as an active learning tool.

1. Introduction

The amalgamation of different disciplines and fields of study can benefit engineering education. This paper discusses the adoption of system-of-systems (SoS) engineering principles in structural mechanics education. The two fields (i.e., SoS and structural mechanics) may appear to be completely different subjects at first glance. However, when we look at the two fields carefully, we realize certain similarities exist. For instance, both fields involve studying and analyzing the behavior and response of complex systems and structures. Both fields consider factors such as material selection and manufacturing processes. We use mathematical models and computational tools in both fields to understand and predict the systems and structures' behavior based on various inputs. Also, both fields aim to optimize the performance of the systems/structures to ensure better safety and reliability while mitigating the risk of failure.

Despite the similarities, wherein both fields deal with the design and analysis of systems, there are some critical differences in their focus and approach. SoS engineering is a broad discipline encompassing various aspects of designing and managing complex systems. SoS engineering manages the product from the beginning (i.e., brainstorming and idea conception) to the end (i.e., product obsolete and retirement) of the product lifecycle. Also, SoS considers technical and non-technical factors, including risk appetite assessment, cost improvement, and operational schedule disruptions. Thus, SoS engineering takes a holistic and comprehensive approach to systems design, development, and operation. On the other hand, structural mechanics is physics that studies how motion and forces affect the deformable body. Thus, structural mechanics focuses on understanding physical laws that govern solid objects' behavior and applying these principles to analyze and predict the response of materials and structures under various loads. That is, while SoS and structural mechanics are concerned with the behavior of systems, the former focuses on the overall design, management, and implementation of complex systems. The latter focuses on studying physical laws and their application to specific components and structures within the system.

This paper proposes using the SoS principles in structural mechanics education. By exploring the SoS principles for structural mechanics education, engineering educators can use the SoS-inspired framework in their pedagogy to provide a better educational experience for engineering students in structural mechanics courses.

2. Background and Literature Review

The field of SoS is complex and interdisciplinary. The SoS refers to a conglomerate of multiple subsystems within an extensive system to achieve goals collectively [1], [2]. Each subsystem in the overall system may be unique and dependent on other subsystems [3]. SoS engineers understand the system, create a model to describe the system mathematically, and create software tools (e.g., decision-support software) to help assist the decision-making process [4], [5]. Even though working with a complex system is challenging, SoS engineers streamline the approach to obtain the results. This section discusses the two fundamental concepts necessary for implementing the SoS-inspired framework in structural mechanics education: 2.1 Define, Abstract, and Implement (DAI) and 2.2 Zone of Proximal Development (ZPD).

2.1 A System-of-Systems Inspired Framework: Define, Abstract, and Implement (DAI)

SoS engineers work on "messy" problems. The engineers create a framework to define and formulate problems based on a chaotic system that appears to be unpredictable. Complexity arises from interactions among the system components, especially when the interactions are nonlinear. SoS engineers use mathematics to model the systems. Then, based on the initial conditions, the engineers predict future behavior based on the stakeholders' risk appetite. One of the approaches that SoS engineers use is a top-down waterfall approach. The approach is called the Definition, Abstraction, and Implementation (DAI) method [6], [7], [8], [9] (Figure 1).

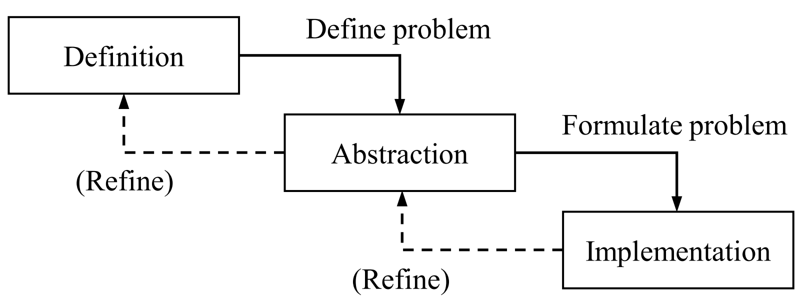

Figure 1. SoS DAI Top-Down Waterfall Approach

The DAI approach is effectively a streamlined version of "the big picture to the small picture" approach, where the process starts with the definition (i.e., understanding the problem), abstraction (i.e., identifying the problem), and implementation (i.e., generating a solution). Seeing the big picture is essential in SoS because having a broader system perspective allows SoS engineers to understand the context, implications, and interrelations between subsystems.

The SoS DAI top-down approach also allows the SoS engineers to see trends and patterns, which will become important when making decisions.

The first phase, the Definition phase, involves defining the system, project, or problem to be solved. The process includes gathering requirements, defining the objective, and determining constraints. To this end, SoS engineers use a tool called Model-based Systems Engineering (MBSE). MBSE considers the given system as a whole and utilizes a set of models to represent various aspects of the system. The trend in SoS is to use MBSE and Authoritative Source of Truth as core digital engineering strategies to manage a large complex SoS and integrated product life cycle and supply chain management [10], [11], [12].

In the second phase, the Abstraction phase, the system, project, and/or problem are abstracted into a solution [13]. To this end, engineers decompose the system into smaller, more manageable subsystems. In this way, SoS engineers can define the high-level framework (i.e., a model) that addresses the given system to seek emergent behavior. This phase also identifies how subsystems are related, thereby defining the interdependencies within the system.

The third phase, the Implementation phase, uses the conceptual abstraction of the system from the previous phase as a surrogate model and creates a software tool or a conglomerate of software tools (i.e., software suite) for the stakeholder [14]. Since this is the last step, the solution must be validated and refined so that the final solution conforms to the defined requirements from the first phase.

As shown above, the SoS DAI process applies a methodological approach to designing, managing, and integrating complex systems. SoS engineering promotes a model-based approach, thereby creating a set of rules to organize, manage, and optimize a system. The urgency to implement the SoS DAI process affects the approach as well. For instance, if the system we are trying to improve needs some extra time (e.g., several decades to complete), an SoS-inspired approach could start with obtaining suggestions on the future direction from a knowledgeable group of technical folks [15] and move the DAI process slowly and steadily.

On the other hand, if this is a time-sensitive topic (e.g., several hours to several days to complete) like mission engineering, which is one of the required fields of SoS engineering in defense applications, we will need a well-defined process so that we can execute the SoS DAI process fast. The mission engineering process starts by defining the overall system via the Operational View-1 (OV-1) diagram [16]. The OV-1 diagram is a high-level graphic of the system that allows the stakeholder to focus on the operational aspects of the system [17]. The OV-1 provides the operating system's overall scheme and attack structure with a high-level description of the architecture and the method of the mission [17]. Based on the OV diagrams, mission engineers follow a six-step process called "F2T2EA" (i.e., Find, Fix, Track Target, Engage, and Assess) to create a "kill chain" [18]. Thus, in time-sensitive cases, the SoS DAI process moves from the high-level (i.e., OV-1) to the low-level (i.e., F2T2EA) to solve systems engineering problems fast.

To summarize Section 2.1, we reviewed the SoS DAI top-down waterfall approach. SoS engineers streamlined the problem-solving process to follow the DAI format (i.e., going from the

OV-1 diagram to F2T2EA in defense applications in mission engineering). That is, problem-solving in SoS engineering is about creating a framework for a systematic approach. Therefore, we want to introduce the SoS-inspired framework to structural mechanics education to enhance its efficiency.

2.2 Zone of Proximal Development

The target student audience for the research is those in the Zone of Proximal Development (ZPD) [19],[20],[21] in the structural mechanics learning environment. The ZPD refers to a concept where some learners can independently learn the subject, whereas others can develop skills only if more knowledgeable mentors (e.g., experienced instructors) can provide guidance and support, as shown in Figure 2. To this end, ZPD has already been applied to engineering education and the scholarship of teaching and learning [22], [23], [24].

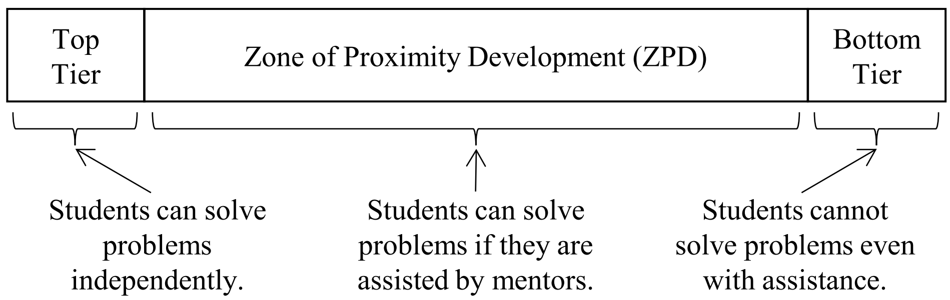

Figure 2. Zone of Proximity Development

When we observe students in the ZPD domain, as opposed to the top tier, the ZPD group often contains students with lower native problem-solving abilities [25]. This is an empirical observation during the structural mechanics course's recitation sessions (i.e., instructor-led problem-solving sessions) [26]. Moreover, while working with students during the recitation sessions [27], we observed that a clear and systematic approach, as observed in SoS problems, is essential for those in the ZPD as they struggle with the steps in solving mechanics problems. Recognizing the ZPD for instructors has advantages. First, instructors can identify/gauge the level of challenges appropriate for students. If the level of material is too difficult, instructors can dial down. If the material level is too easy, the instructor can make it more challenging. This way, instructors can provide appropriate support, guidance, and mentorship to students for their learning process [28]. Instructors can also promote active learning by working within the ZPD group.

Furthermore, working within ZPD allows students to communicate with each other and instructors. It creates a synergetic learning environment where students are encouraged to collaborate, share ideas, and solve problems. Thus, this will create healthy collaboration among the learners and between students and instructors [26], [27]. Finally, by providing the appropriate level of subject matter based on the ZPD, students can challenge themselves (and the level of challenge is appropriate). Thus, the ZPD encourages students to go beyond basic comprehension and information from the classroom to engage in more complex cognitive activities that require analysis, synthesis, evaluation, and creativity [29], [30], [31].

To summarize Section 2.2, we reviewed ZPD and why it matters for effective education. By combining ZPD with the SoS-inspired framework discussed in Section 2.1, we want to apply SoS engineering's top-down approach to structural mechanics education in order to improve the quality of the teaching and learning process.

3. Description of the Course

Structural Analysis I (AAE 35200) is a three-credit lecture course in aerospace structural mechanics course in the School of Aeronautics and Astronautics at Purdue University [26], [27]. Table 1 shows the lecture topics that follow the course textbook [32]. Typically, there are twelve homework assignments, with each chapter covering one to three homework assignments. In the Summer 2021 and Fall 2021 semesters, 47 and 99 students took the course, respectively. During the Summer 2021 semester, the students took the course four times weekly on Mondays, Tuesdays, Wednesdays, and Thursdays for 75 minutes per lecture online (i.e., no in-person course) for the eight-week semester. During the Fall 2021 semester, the students took the course three times per week on Mondays, Wednesdays, and Fridays for 50 minutes per lecture via a hybrid of online and in-person for the 16-week semester.

Table 1. AAE 35200 Course Topics

Course Topics
Chapter 1 Aircraft Structures and Materials • A brief review of aircraft structural function and load transfer • Review of basic structural elements (bars, panels, beams, shafts) • Introduction of mechanical properties of aircraft materials • Geometric properties of structural components
Chapter 2 Elasticity • Displacement, strain, and stress distributions • Free-body diagrams and static equilibrium conditions • Linear stress-strain relations and energy methods • Plane elasticity
Chapter 3 Torsion • Deformation of shafts with circular cross sections under twisting • Shafts with more complicated cross sections • Warping of cross sections • Constraint effects
Chapter 4 Bending and Flexural Shear • Simple beams • Multiaxial bending • Transverse shear in beams • Deformation of thin-walled beams
Chapter 5 Shear Flow in Thin-Walled Sections • Concept of shear flow • Shear center • Combined Flexural Torsional Shear Flow • More complicated cross sections
Chapter 6 Failure Behavior of Isotropic Materials • Failure of brittle materials • Yielding of ductile materials • Fatigue and fracture (if the time allows) • Stress intensity factor (if the time allows)

AAE 35200 may be taken with AAE 35201, a hands-on lab accompanying the contents of AAE 35200. For further details on the AAE 35200 course, readers can refer to previously published papers [26], [27]. For further details on the AAE 35201 course, readers can refer to previously published papers [33], [34].

4. Methods

Mechanics educators often face challenges working with undergraduate students with limited exposure to mechanics problems. Some of the potential reasons for these challenges are as follows: (1) Students may lack the fundamental knowledge necessary to solve problems. (2) Students may have issues with skills related to their quantitative reasoning, which is an essential ability to interpret a complex problem, analyze the given numerical/mathematical information, and utilizes the information to make informed decisions when solving problems. (3) Students may also have difficulty developing abstract thinking as mechanics problems often require problem-solving skills rooted in abstract thinking. (4) Students may lack problem-solving skills (i.e., native problem-solving ability). The lack of skills could result from weak math/science foundations, insufficient practice, or lack of skills to translate the knowledge they learned from one problem to another similar but slightly different problem. (5) Students may have low confidence as they struggle with challenging problems, which results in low confidence and reduced motivation to deal with complex problems and engagement in the course activities. As discussed earlier, some of the difficulties are experienced by students in the ZPD.

4.1 Definition (D)

We can learn a practical and methodological lesson in SoS engineering's top-down approach when considering how to effectively teach mechanics problems to engineering students. To this end, we can apply the top-down approach in SoS engineering to mechanics education, especially for undergraduate students whose problem-solving skills have not yet been fully developed.

We previously discussed how SoS engineers, especially those in the mission engineering discipline, use the OV diagrams to visualize the mission thread going from the large picture (i.e., OV diagrams) to the smaller picture (i.e., kill chain details) to solve the problem. Parallel to this methodological approach, in structural mechanics problems (e.g., a truss member), structural engineers and students can see the large view of the problem by looking at the entire structure as a whole and writing down what is given ("given"). Then, the students write down what they want to achieve in the form of a requirement ("required"). Then, upon careful observation of the loaded state and boundary conditions, the structural engineers and engineering students can start solving the problem ("solution") by completing a free-body diagram to visualize the reaction forces and moments. At this point, the student's objective is to find these unknowns to solve the structural mechanics problem.

When dealing with undergraduate students with limited exposure to mechanics problems, one of the first observations is that some students are trying to solve the problem without clearly understanding the given problem, defining the requirements, or knowing what they are trying to solve. Thus, the first step of the large picture is missing. Thus, as stated above, mandating the "given," "required," and "solution" in students' exercises will help achieve this goal. From this point, as students start abstracting problems, we provide further assistance to students with specific knowledge of mechanics. For instance, if an example problem is with a stringer-web open cross, the students must sketch the provided cross section and write down the cross sectional area of the stringers since these will become critical information later. In the second step (i.e., "required"), students identify what is required to solve this problem. For instance, if the problem asks for the centroid locations, the area moment of inertia, or the shear flow, students need to write them down under "required." In the third step (i.e., "solution"), students can start writing the solution after entering all the given and required information.

As students try to solve different cross sections, they are confused due to the complexity of various cross sections and requirements. At this stage, students can ask themselves the following questions:

- Is this an open or closed cross section?
  - If the cross section is closed, a fictitious is necessary (thus, provide one)
- Does the problem have multiple cells or a single cell?
  - If multiple cells are given with closed cross sections, the number of fictitious cuts equals the number of cells.
- Does the cross section contain stringers?
  - If the problem is stringer-web, students may assume that thin sheets (webs) are ineffective in bending; therefore, shear flow is constant between stringers.
- Is the cross section symmetric or unsymmetric?
  - If the given cross section is symmetric, the product of inertia with respect to the horizontal and vertical axes is zero (i.e., $I_{xy} = 0$). Thus, students may use the simplified calculation method for the symmetric cross section. Alternatively, students can also use the calculation method for the unsymmetric cross sections, which will be reduced to the calculation method for the symmetric cross section after substituting $I_{xy} = 0$.
  - If the given cross section is unsymmetric, the product of inertia with respect to the horizontal and vertical axes is non-zero (i.e., $I_{xy} \neq 0$). Thus, students need to use the calculation method for the unsymmetric cross section.
- What is the requirement of this problem?
  - Are we calculating the shear center location?
  - Are we obtaining shear flow?
  - Are we calculating twist angle per unit length?

4.2 Abstraction (A)

Based on the previous Definition section exercise, students can start formulating the problem. As discussed in the Background section, SoS engineering starts with defining a system (large picture). The process becomes streamlined as the analysis matures and the systems' behavior is well understood. To this end, we can establish a streamlined process in mechanics education from the students' learning standpoint. Understanding the behavior of a hollow cross section is crucial in dealing with the behavior of aircraft structures since aircraft members are hollow cross sections.

As we teach the structure with hollow cross sections, one of the first obstacles is calculating the centroid and the area moment of inertia. These cross sectional property calculations are the first step in calculating more complex topics like shear flow and shear center. Another example is calculating the area moment of inertia (i.e., the second moment of area) for a cross section with complex geometry like a stringer-web cross section for an aircraft wing. In this problem, students are supposed to use a two-step process. First, students calculate the location of the centroid in the cross section by using the first moment of area on the temporary coordinate system that is placed at a known location, like a particular stringer location. Second, after determining the centroid location, students place the permanent coordinate with the centroid as the origin of this new coordinate. Then, using the permanent coordinate system, students calculate the area moment of inertia using the parallel axis theorem.

4.3 Implementation (I)

The authors propose the "two-table approach." In this approach, the first table allows students to calculate the location of the centroid using the first moments of the area. Then, using the parallel axis theorem, the second table allows students to calculate the area moments of inertia (i.e., the second moments of area) and the product of inertia. As a result, the calculation of the cross sectional properties is condensed into simply creating/filling out two tables regardless of how complicated the cross section appears.

Calculating the cross sectional properties (i.e., centroid and area moment of inertia) requires significant student effort if the students try to solve problems randomly without knowing much about its procedure. However, by streamlining the process using the two-table approach, as described above, the students can formulate the structural mechanics problem much easier while mitigating the risk of errors. Thus, this is an application of SoS engineering principles of creating rules to organize the given system.

5. Results and Discussion

Streamlining the engineering problem solving process involves identifying all calculation steps and analyzing their effectiveness to a) eliminate all unnecessary steps and 2) optimize the process efficiency and productivity. As a result, the overall process will be faster and easier for students. This process provides a clear and systematic approach inspired by the SoS DAI framework and is essential for those students in the ZPD. The intended objective of this research is to apply the SoS engineering approach to mechanics education to create something concrete so that both educators and students can improve the quality of the teaching and learning process in mechanics education. This section describes examples of SoS engineering applications in mechanics education using an AAE 35200 example problem as a use case.

AAE 35200 involves the calculation of hollow cross sections. The calculation of cross sectional properties for hollow cross sections is much more complicated than those of solid cross sections since there are infinite numbers of arbitrary shapes for hollow cross sections. In contrast, the standard forms of solid cross sectional shapes are limited (e.g., a rectangle and circle). As a result, there are no tabular charts/guidelines to calculate cross sectional properties for hollow cross sections like those we can find for the solid cross sections on the back of many textbooks.

Therefore, we need to create a step-by-step process for calculating the cross sectional properties of hollow cross sections. Then, we need to demonstrate the process to the student so that they can follow the procedures. The streamlined process for a typical structural mechanics problem is summarized in the bullet points below.

- Step 1: Identify "given," "required," and "solution" using the suggested summary table.
- Step 2: Sketch the cross sectional diagrams.
- Step 3: Specify the temporary coordinate system (i.e., the $\bar{y}$–$\bar{z}$ coordinate system).
- Step 4: Find the centroid of the cross section with respect to the $\bar{y}$–$\bar{z}$ coordinate system using the first moments of area and the two-table approach (use the first table of the two tables).
- Step 5: Convert the stringer locations to the centroidal coordinate system (i.e., the y–z coordinate system).
- Step 6: Find the area moments of inertia and the product of inertia using the two-table approach (use the second table of the two tables).
- Step 7: Find required information like the shear flows, shear center, shear stress, bending stress, and twist angle per unit length (not covered in this paper).

The following sections examine two examples (i.e., the summary-table approach and the two-table approach) of how the SoS-inspired streamlined process should look when solving a hollow cross section problem. Section 5.1 expands Step 1 in the bullet point above and uses the summary table to assist students' self-study on dealing with diverse types of problem-solving and identify the given, required, and solution for the example problem. Sections 5.2 and 5.3 expand Steps 2–6 in the bullet point above and use the "two-table approach" to assist students in calculating the centroid and the area moment of inertia. Finally, Section 5.4 will provide the general problem solving approach and why the SoS-inspired streamlined approach makes sense more than the other method (i.e., compartmentalization) when managing complex problems.

5.1 D: Define the Structural Mechanics Problems

Engineers with SoS expertise can create and use frameworks to manage complex problems. To this end, the mechanics educator can do the same: Create a good framework for students in the ZPD to study using the "summary table." To alleviate the headache and streamline the thought process, a summary table (Table 2) of homework exercise problems is especially useful for students with little training in mechanics (i.e., students in the ZPD domain).

Based on the ZPD analysis of the instructors, they can decide how to introduce the summary tables and who should create the summary table. For instance, if the students are in the upper portion of the ZPD domain, the students can create the summary table independently. If the students are in the middle portion of the ZPD, instructors can provide a half-filled table so that students can fill out the rest. If the students are in the lower portion of the ZPD (thus, struggling to approach the problem), instructors can provide the complete table so that it gives motivation to the students to solve mechanics problems.

These are some of the possibilities of how mechanics instructors can assist students' learning process depending on where the students are located in the ZPD domain. However, providing different versions of the summary table within the same semester will cause some confusion among the students since it gives a sense of unfairness among them. Therefore, if an instructor wants to know the level of students and/or wants to conduct the Scholarship of Teaching and Learning (SoTL) research by providing different versions of summary tables, the instructor should 1) stick to one version of the summary table per semester and 2) provide different versions in the following semesters (while still using one version per semester) to see how different versions of summary table affect the academic performance of students.

Table 2. Example of a Table Summarizing the Characteristics of Cross Sectional Area

Problem	Given				Required
	Open or Closed	Single or Multi Cell	Stringer-web or Thin-walled	Symmetric or Unsymmetric	
5.1	Open	Single	Thin-walled	Symmetric	q
5.2	Open	Single	Thin-walled	Symmetric	q
5.3.1	Open	Single	Thin-walled	Symmetric	y_{sc}
5.3.2	Open	Single	Stringer-web	Symmetric	y_{sc}
5.5	Closed	Single	Stringer-web	Symmetric	q, θ, y_{sc}
5.7	Open	Single	Stringer-web	Unsymmetric	q
5.8	Open	Single	Stringer-web	Unsymmetric	y_{sc}, z_{sc}
5.10	Closed	Multi	Stringer-web	Symmetric	q, θ
5.11	Closed	Multi	Stringer-web	Symmetric	q, θ
5.13	Closed	Single	Thin-walled	Symmetric	q
5.14	Closed	Single	Stringer-web	Symmetric	y_{sc}
5.15	Closed	Multi	Stringer-web	Unsymmetric	q, y_{sc}

Description: The problem column shows the problem numbers given in the textbook [32]; Open = open cross section, Closed = closed cross section, Single = single cell, Multi = multi cell, Thin-walled = cross section with thin-walls (without stringer-web), Stringer-web = cross section with stringer-web/skin cross section), Symmetric = cross section with at least one axis of symmetry; Unsymmetric = cross section without the axis of symmetry; q = shear flow, y_{sc} = horizontal shear center location, z_{sc} = vertical shear center location, θ = twist angle per unit length.

Let us now consider a more specific structural problem. Figure 3 (a) shows a notional example problem with a P-shaped stringer-web open cross section. The dimensions of the cross section are provided as shown. Also, the cross sectional area of each stringer is given 5.0×10^{-4} (m^2).

Given Figure 3 (a), we pose the following questions to students. As an outcome, students can create a summary table, as shown in Table 3.

- Is this an open or closed cross section?
  - Answer: Open
- Is the provided cross section multiple-cell or a single-cell?
  - Answer: Single cell
- Does the cross section contain stringers?
  - Answer: Yes, this is a stringer-web cross section
- Is the cross section symmetric or unsymmetric?
  - Answer: Unsymmetric
- What is the requirement of this problem?
  - Answer: We need to obtain shear flow (q) in each domain

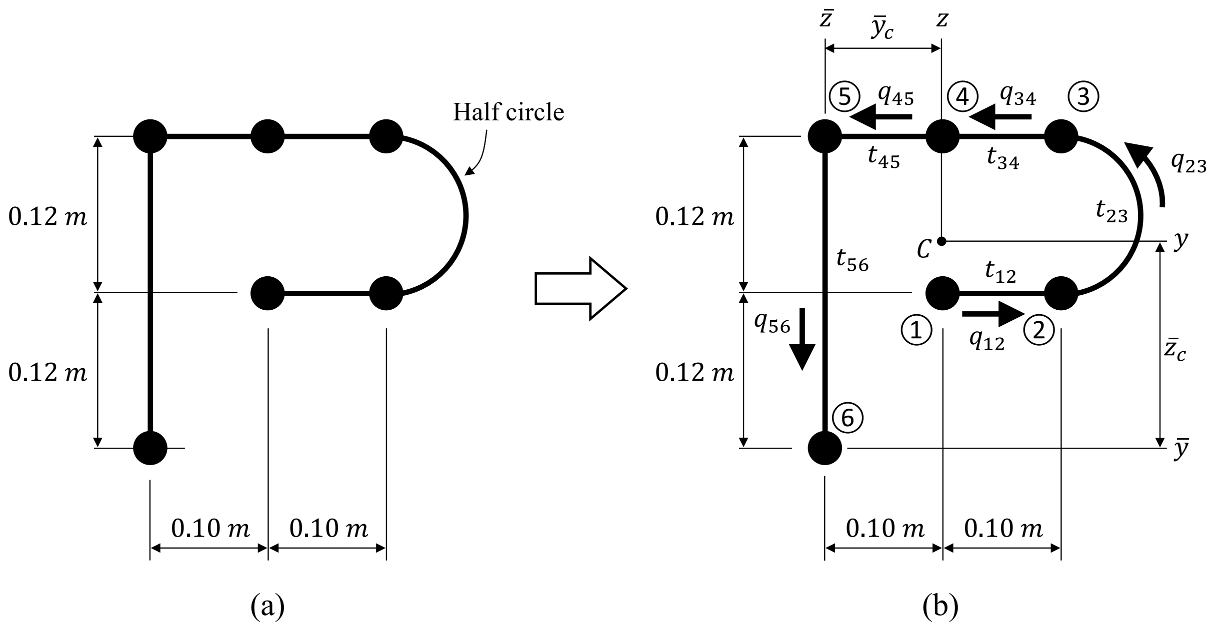

Figure 3. A Notional Example of a P-Shaped Stringer-Web Open Cross Section: (a) Before ("As Given" by the Instructor to Students) and (b) After (Details Entered by Students)

Table 3. Summary Table for the Given Problem (Figure 3)

Problem	Given				Required
	Open or Closed	Single or Multi Cell	Stringer-web or Thin-walled	Symmetric or Unsymmetric	
Figure 3	Open	Single	Stringer-web	Unsymmetric	q

5.2 A: Formulate the Cross Sectional Property Calculation

When students see the problem as given in Figure 3 (a), their first reaction is slightly confused about where to start. The first step is to instruct students to specify all necessary details to the provided cross section so that students have the necessary information to solve the problem, as shown in Figure 3 (b). At this stage, instructors can provide the following narrative and instructions for obtaining the cross sectional properties.

Students must set up two coordinate systems to properly prepare the updated figure, as Figure 3 (b) depicts. A temporary coordinate system (i.e., the $\bar{y}$–$\bar{z}$ coordinate system) and centroidal coordinate system (i.e., the y–z coordinate system). To sketch the centroidal coordinate system, students must write a centroid (C) as a dot on the figure. At this point, we do not know where the centroid is located. Thus, students can select an arbitrary location for the centroid. Students can also write stringer numbers (i.e., 1–6) and shear flow arrows (i.e., q_{12} to q_{56}). If the problem asks for shear stress, the thickness of the web becomes essential. Thus, students can write the nomenclature for the thickness of each section as well (i.e., t_{12} to t_{56}).

Based on the temporary coordinate system and the arbitrarily-selected centroid location, students can specify the centroidal coordinate ($\bar{y}_c$, $\bar{z}_c$) with respect to the temporary coordinate system using Equations (1) and (2), where $n = 6$ since there are six stringers.

$$\bar{y}_c = \frac{\sum_{i=1}^{n} A_i \bar{y}_i}{\sum_{i=1}^{n} A_i} \tag{1}$$

$$\bar{z}_c = \frac{\sum_{i=1}^{n} A_i \bar{z}_i}{\sum_{i=1}^{n} A_i} \tag{2}$$

After students obtain the centroidal coordinate ($\bar{y}_c$, $\bar{z}_c$) with respect to the temporary coordinate system, all stringer locations will need to be expressed in terms of the centroidal coordinate system. Then, using the parallel axis theorem, students can obtain the area moments of inertia (I_y and I_z) and product of inertia (I_{yz}), where $n = 1$. Please note that Equations (3), (4), and (5) only use the second-term values and do not use the first term in the parallel axis theorem. Per the textbook [32] for this course, the first-term values (i.e., the moment of inertia ($I_{y_c i}$, $I_{z_c i}$, and $I_{yz_c i}$ for Equations (3), (4), and (5), respectively) about the centroid of each stringer) are a few orders of magnitude smaller than the second-term values. Thus, we can disregard the first-term values.

$$I_y = \sum_{i=1}^{n} A_i {z_i}^2 \tag{3}$$

$$I_z = \sum_{i=1}^{n} A_i {y_i}^2 \tag{4}$$

$$I_{yz} = \sum_{i=1}^{n} A_i y_i z_i \tag{5}$$

Furthermore, when students formulate the shear flow equation for open vs. closed sections, the former (i.e., an open section) does not require a fictitious cut since the cross section is already open. On the other hand, the latter (i.e., a closed section) requires the fictitious cut so that the closed cross section will need to be treated as an artificial "open" section to solve the problem.

5.3 I: Obtain Cross Sectional Properties Using the "Two-Table" Approach

We are ready to move to the next step, the Implementation phase. In the implementation phase, we propose using the "two-table" approach. In this approach, we ask students to prepare two tables. The objective of the first table is to obtain the centroid location of the cross section. The objective of the second table is to obtain the area moments of inertia and the product of inertia. Thus, students can obtain the cross sectional properties necessary for calculating the shear flows after completing the two tables.

5.3.1 First Table: Obtain the Centroid Location ($\bar{y}_c$ and $\bar{z}_c$)

Students create the first table (Table 4) using the temporary coordinate system (i.e., the $\bar{y}$–$\bar{z}$ coordinate system), as described in the previous section. Using the table and Equations (1) and (2), students can calculate the centroid location ($\bar{y}_c$ and $\bar{z}_c$). The results of Equations (1) and (2) in the example are $\bar{y}_c = 0.10\ (m)$ and $\bar{z}_c = 0.16\ (m)$, respectively.

Table 4. The First Table for $\bar{y}_c$ and $\bar{z}_c$

Stringer No.	A_i (m^2)	$\bar{y}_i$, Horizontal Location (m)	$\bar{z}_i$, Vertical Location (m)	$A_i\bar{y}_i$ (m^3)	$A_i\bar{z}_i$ (m^3)
1	5.0×10^{-4}	0.10	0.12	5.0×10^{-5}	6.0×10^{-5}
2	5.0×10^{-4}	0.20	0.12	10.0×10^{-5}	6.0×10^{-5}
3	5.0×10^{-4}	0.20	0.24	10.0×10^{-5}	12.0×10^{-5}
4	5.0×10^{-4}	0.10	0.24	5.0×10^{-5}	12.0×10^{-5}
5	5.0×10^{-4}	0	0.24	0	12.0×10^{-5}
6	5.0×10^{-4}	0	0	0	0
Σ Sum	30.0×10^{-4}	-	-	3.0×10^{-4}	4.8×10^{-4}

5.3.2 Second Table: Obtain the Area Moments of Inertia (I_y and I_z) and Product of Inertia (I_{yz})

After obtaining the centroid location, students can create the second table (Table 5) using the centroidal coordinate system (i.e., the y–z coordinate system). Using the second table (Table 5) and Equations (3)–(5), students can calculate the area moments of inertia and the product of inertia. The results of Equations (3)–(5) in the example are $I_y = 2.4 \times 10^{-5}$ (m^4), $I_z = 2.0 \times 10^{-5}$ (m^4), and $I_{yz} = 6.0 \times 10^{-6}$ (m^4), respectively. Students can now use the calculated I_y, I_z, and I_{yz} values to calculate the shear flows (i.e., q_{12} to q_{56}).

Table 5. The Second Table for I_y, I_z, and I_{yz}

Stringer No.	A_i (m^2)	y_i, Horizontal Location (m)	z_i, Vertical Location (m)	$A_i{z_i}^2$ (m^4)	$A_i{y_i}^2$ (m^4)	$A_iy_iz_i$ (m^4)
1	5.0×10^{-4}	0	-0.04	8.0×10^{-7}	0	
2	5.0×10^{-4}	0.10	-0.04	8.0×10^{-7}	5.0×10^{-6}	-2.0×10^{-6}
3	5.0×10^{-4}	0.10	0.08	3.2×10^{-6}	5.0×10^{-6}	4.0×10^{-6}
4	5.0×10^{-4}	0	0.08	3.2×10^{-6}	0	0
5	5.0×10^{-4}	-0.10	0.08	3.2×10^{-6}	5.0×10^{-6}	-4.0×10^{-6}
6	5.0×10^{-4}	-0.10	-0.16	1.28×10^{-5}	5.0×10^{-6}	8.0×10^{-6}
Σ Sum	-	-	-	2.4×10^{-5}	2.0×10^{-5}	6.0×10^{-6}

5.4 General Problem Solving Approach

It is crucial for the SoS-inspired streamlined approach to go from "the big picture to the small picture." To this end, in Section 5.1, we posed a set of questions to define the cross sections and introduced the summary table to organize and visualize the problem. Sections 5.2 and 5.3 used the two-table approach to standardize the approach in solving the cross sectional properties using the example problem. These are our attempts to streamline the structural mechanics problems for engineering education using the SoS-inspired framework. This section will review engineering problem solutions from a larger/more generalized problem solving viewpoint. Thus, the readers can relate to their engineering education experience and understand why the SoS-inspired streamlined approach in their engineering education practices makes sense more than the other method (i.e., compartmentalizing) when managing large complex problems.

Although streamlining and compartmentalizing both refer to problem solving techniques, the former involves simplifying and optimizing a system to make it more efficient. Thus, identifying and eliminating unnecessary components in the system becomes crucial for the outcome. As a result, the focus of streamlining is on complexity reduction. On the other hand, the latter involves breaking down a complex system into smaller components so that they become manageable. This approach involves identifying key components so that the problem solver can address each key component independently. As a result, the focus of compartmentalization is on complexity elimination.

In most structural mechanics problems (and many engineering problems), compartmentalization is not the most suitable option since it tends to assume that each key idea/each subsystem is independent and fragmentary [35], [36]. In many engineering problems, however, one segment of a system depends on other segments of the system. In fact, dependencies between subsystems can significantly affect the behavior of the whole structure [37]. Therefore, we need to solve the problem as a whole, which is the very definition of SoS, where subsystems interact to achieve a common goal [1], [2]. Thus, it is in the best interest of engineering educators to use the streamlining technique to manage complex problems via the SoS DAI framework, discussed in Sections 2.1 (Background), 4.1–4.3 (Methods), and 5.1–5.3 (Results).

6. Conclusions and Future Work

We initiated the SoS-inspired framework to enhance aerospace structural mechanics education. The SoS-inspired DAI framework has the possibility to become an active learning pedagogy since the framework can be adjusted to fit the students right in the ZPD domain. An adequately adjusted problem can create healthy collaboration among the learners as well as between students and instructors. The DAI approach is also a streamlined version of "the big picture to the small picture" approach, so the students can always see the big picture, which helps them understand how everything fits together and fosters creativity.

For future work, we would like to seek different examples of structural mechanics problems to demonstrate the use of the SoS-inspired framework, for instance, optimization of the stress distribution and part weight reduction. Moreover, combining the SoS-inspired approach with digital teaching techniques like virtual lab [33], [34], [38], [39], [40] could be an exciting topic since the interactive and multimedia nature of the teaching and learning environment appeals to today's students who are comfortable with using the digital media as a learning tool. Finally, we are interested in conducting additional SoTL research on how SoS-inspired mechanics education, combined with digital technology, affects students' understanding of the topics. The results of the SoTL research will generate statistical analysis and data on the effectiveness of the SoS-inspired framework in mechanics education.

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