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RESEARCH ARTICLE

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An Excel-based approach for designing stepped driveshafts for mobility devices and a study of its use in a design of machine elements course

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Abstract

The aim of this paper is to describe a new MS Excel-based approach for designing driveshafts for stiffness and fatigue strength. We analyze the efficacy of the approach in engaging students in an iterative design process and higher-level qualitative decision-making activities in an undergraduate class at Texas A&M University. Compared to conventional fixed cross-section frames and trusses, there are few tools (barring Finite Element Packages) that facilitate rapid design evaluations of stepped shafts. The approach is based on a novel use of singularity functions to obtain explicit solutions for stepped shafts under concentrated loads. This approach allows for relatively easy implementation into Excel without the need for any numerical integration or other forms of approximation. Currently, the tedious calculations involved in the design of stepped shafts prevent instructors from exploring iterative changes in driveshaft design. The Excel tool that we have developed allows instructors and students to focus on iterative decision-making. With this tool, open-ended design questions are assigned even in exams since the entire iterative process takes less than 15–20 min. Student surveys and analysis of exam answers reveal that students have gained a considerable capability to make design decisions. They also indicate areas where improvement in design thinking is needed.

KEYWORDS

design, drive shaft design, fatigue strength, MS Excel, singularity functions, stepped shaft design

1 | INTRODUCTION

The design of machine elements is an essential course in the mechanical engineering curriculum. It is the culmination of the mechanics coursework that begins with physics mechanics and continues through statics and strength of materials. This is a transition course between pure engineering science and engineering practice. The aim of the course is to enable students to learn how the concepts that they learned in their engineering science (mechanics) courses can be used to design components, such as drive shafts, gears, welds, and so forth. The process of designing such components, as practiced in the real world, is iterative: certain initial guesses are made with regard to the geometry, material, and loads, and the design proceeds by verifying whether they meet the targets in terms of stiffness, strength (both static and fatigue), and stability. The process proceeds by iterating and each step of the iterative decision-making are checked against the criteria.

However, in the classroom, very little "design" can be done using the iterative design process, wherein students make an initial guess of the component geometry, choose material properties and estimate loads, verify whether it meets the stiffness, strength, and stability. The reason is that conventional approaches take too much time to carry out. Also, teachers spend a considerable amount of time helping students with the nitty-gritty of the actual computation of deflections and stresses, and not enough time is spent on the decision-making process. Students come away with the idea that the class is mostly about complex and lengthy calculations instead of design decision-making and interpretation of the results.

This is more evident in the case of stepped shafts. These shafts are the critical components that connect precision-engineered drive parts (gears, chain, sprockets, sheaves for belt drives, bearings, etc.) with the frame. They have very significant time-varying loads and, at the same time, must have excellent dimensional accuracy since the precision parts mounted on them will operate only under stringent deflection and orientation mismatch conditions. Moreover, with the increased interest in autonomous and electric vehicle competitions (ranging from electric bicycles and skateboards to cars, wheelchairs, and other personal mobility devices), there is an upsurge in interest in the design of custom driveshafts. Anecdotally, many student groups have approached the instructors for help in the design of these components.

The design of these shafts is suitable for consideration for the class since they are an illustration of how all the aspects of design are carried out—shaft layout, geometry specification, considerations of deformation, considerations of load and stress concentrations, and so forth. Furthermore, they are seemingly suitable since they involve shear force, bending moment, beam slope, and deflection formulae. For statically determinate beams, the shear force and bending moments (SFD, BMD) are independent of the shaft cross-sections and can easily be computed. However, the same is not valid for the slope and deflections of the beam. For this reason, most textbooks, including Shigley's Mechanical Engineering Design [26] and Fundamentals of Machine Component Design [16] focus on SFD and BMD first and present design problems (where shaft dimensions have to be estimated) purely based on static strength or fatigue strength. The use of singularity functions considerably simplifies the setup for these problems and slope and deflection calculations for shafts with fixed diameters.

However, it is well known that for most applications, gross dimensions of driveshafts are determined by stiffness requirements due to the extremely stringent conditions imposed by gear and bearing alignments. This poses a problem for teaching—the calculations of the deflection and slope of a stepped shaft are very tedious (as opposed to a shaft of constant cross-section). A complete stepped shaft design takes many pages of tedious computation (see Shigley [26]) and so is entirely avoided by many instructors as being too time-consuming. The alternative is to either use Castigliano's theorem (as was done by [22]) or use a numerical solver, like the Finite Element Method (which for all purposes is a black box for the students). In the latter case, in a typical course on the design of machine elements, students fail to decipher how these equations are obtained or derived, so instructors are loathed for simply using it as a black box.

In this paper, we present an alternative approach of using the singularity function method to obtain explicit solutions for the displacements and slopes for stepped shafts and implement this approach in Microsoft Excel. Spreadsheets, such as Excel, offer an extremely attractive alternative to the two extremes—hand calculations or full-fledged solids modeling environment. Even though the use of spreadsheets for calculations has been widely advocated (and routinely used in engineering practice), they are not as widely adopted as one would expect, partly because textbooks tend not to use them.

Niazkar and Afzali [21] have surveyed the use of Excel in a wide variety of fields in engineering. The ability of Excel spreadsheets to provide quality and experiential learning for the students has already been discussed in detail by Baker et al. [2]. Fernández et al. [11] demonstrated that numerical method problems can be solved and graphically represented using the VBA solver in Microsoft Excel, resulting in a higher understanding of the students. Boye et al. [5] pointed out the multiple characteristics of Excel spreadsheets, which makes them one of the best problem-solving applications for engineering problems catering to first-year students. Students can use Excel without the hassle of learning advanced programming skills. Students are less likely to get lost in the intricacies of programming and more focused on understanding the problem at hand. One of the best features of Excel is the ability to instantly vary the charts and graphs when any variable of the equation is changed making the decision-making process more intuitive. Doak et al. [8] use of animated spreadsheets resulted in effective learning for students at the freshman level. Leon et al. [4] used MS Excel to teach numerical solutions of ordinary differential equations owning to its simple interface and versatility allowing students to focus on the algorithm and its implementation. The advantages of using Excel spreadsheets for teaching simulations using spreadsheets have been listed by Evans [10]:

(1) Quick start-up time.

(2) Easy visualization of data.
(3) Dynamic update of graphs and charts allowing users to make changes almost instantly.
(4) Integration of statistical tools and functions.

Bermúdez et al. [3] used Excel spreadsheets for the active teaching of an undergraduate hydraulic engineering course. Excel allowed students to get familiarized with the tools used in professional practice, follow along the calculations, change the variables in the equations/formulae, and see their effects on the result plots. Demir et al [7] illustrated the use of MS Excel tools for designing water distribution networks in environmental engineering education. The authors elucidate that even though MATLAB provides faster solutions than MS Excel VBA, MATLAB is licensed software that is not available to everyone. On the other hand, most of the students own a student license for MS Excel, which provides a user-friendly interface that handles both steady-state and extended period simulation of a given water distribution network. Liu [20] has shown how many aspects of solid mechanics can be taught with Excel. Specifically, they have shown examples of the use of Excel for (a) design of straight shafts, (b) unsymmetrical bending (c). They have also shown how specific finite element programs can be performed in Excel. There are various other examples of using MS Excel spreadsheets in other engineering fields [1,6,12,14,15,18,23,25,27].

However, stepped shafts pose a unique challenge because they are not conventional frames and do not seem amenable to simple frame calculations, and have not been treated in a way that is suitable for use in Excel hitherto. With the approach presented here, the instructor can derive the equations for stepped shafts along the same lines as for a shaft with constant diameters (except for a few additional terms) and also set it up as an Excel program that can solve any stepped shaft problem and plot the SFD, BMD as well as slope and deflection diagrams so that students can see what these shapes are, probe different points directly in the Excel charts, make changes to the dimensions on the fly and see the results—all within Excel. With this, it is now possible to assign stepped shaft design problems to the students and engage them in discussing design tradeoffs.

We illustrate how this approach allows instructors to focus on the decision-making challenges in the design process. We have utilized this method in our Solid Mechanics in Mechanical Design course (Course ID: MEEN 368), which consisted of about 200 students (two sections) in the Fall of 2020, to assign full design problems as homework and also parts of it in exams—with the help of such a spreadsheet, students can carry out a complete stepped shaft design (iteratively choosing dimensions and checking for the satisfaction of slope and deflection constraints) in 40 min or less.

The rest of the paper is structured as the following: Section 2 provides an overview, implementation, and pedagogical issues of the current methods that are used in solving stepped shaft problems. Section 3 details the use of the singularity function for solving stepped shaft problems and its implementation in MS Excel. Section 4 assesses the use of Excel for solving the problem and conclusions are given in Section 5.

2 | OVERVIEW OF CURRENT METHODS

To illustrate the current approach and its contrast with available strategies, we consider an example of a stepped shaft in Figure 1. The dimensions of the stepped shaft are given in Table 1. To solve the problem in Figure 1, we describe the outlines of four methods that are typically taught in a Strength of Materials course: (a) Piecewise integration; (b) using Castigliano's theorem [9]; (c) Superposition; and (d) Finite Element Method. We then describe the singularity function approach for stepped shafts and demonstrate the simplicity of the method, especially with Excel. The governing equations for the shaft derived from the Euler–Bernoulli beam theory are [26]:

$$V_y = -\int p_y(x) \quad dx, V_{y|\text{end}} = 0 \quad \text{Force} \quad \text{Equilibrium}, \tag{1}$$

$$M_z = -\int V_y(x) + c_z \quad dx, M_{z|\text{end}} = 0 \quad \text{Moment} \quad \text{Equilibrium}, \tag{2}$$

$$\theta_z = \int \frac{M_z}{EI} dx + a_1 \quad \text{Constitutive} \quad \text{Relation}, \tag{3}$$

$$u_y = \int \theta_z \quad dx + a_2 \text{Kinematical} \quad \text{Compatibility}, \tag{4}$$

where $p_y(x)$ is the distributed transverse load on the beam, V_y is the shear force on the beam cross-section, M_z is the internal bending moment, θ_z is the cross-sectional rotation, and u_y is the displacement of the beam. Also, E is the Young's Modulus, and I is the cross-sectional moment of inertia. When I is constant, the resulting equations are trivial to solve by integration and can also be easily automated, and have been implemented as an educational tool for teaching structural analysis (see e.g., [17,19]).

When applied to a stepped shaft problem, the challenges arise with the last two equations where the

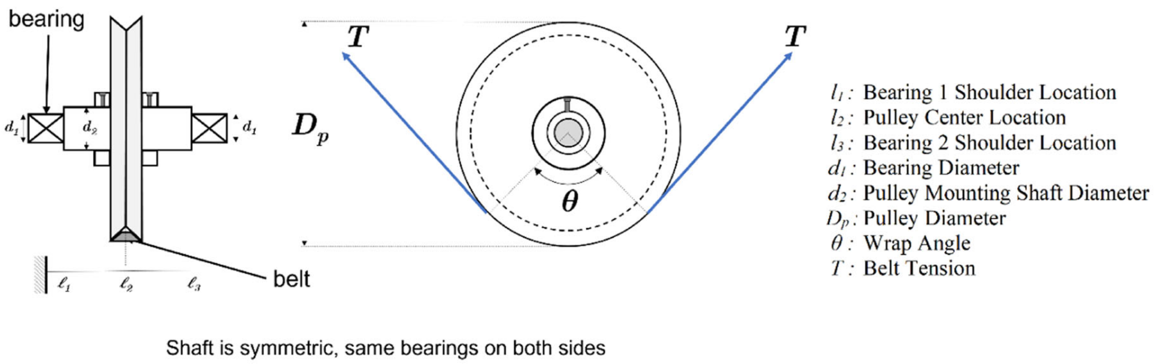

FIGURE 1 A shaft for an idler pulley with two steps.

TABLE 1 Dimensions of the stepped shaft in Figure 1.

Description	Symbol	Value
Bearing 1 shoulder location	l_1	15 mm
Pulley center location	l_2	35 mm
Bearing 2 shoulder location	l_3	55 mm
Bearing diameter	d_1	20 mm
Pulley mounting shaft diameter	d_2	22 mm
Pulley diameter	D_p	120 mm
Wrap angle	θ	60°
Belt tension	T	0.75 kN

term EI is now piecewise constant and creates quite a complex problem. We will now review some common approaches that are used for analyzing this critical structural member.

2.1 | Piecewise direct integration method

This is a relatively straightforward method using the basic equations of straight beams [13]. Since the beam is statically determinate, the bending moment $M(x)$ is independent of the shaft diameters and is computed directly. Using equation (3) and integrating it with respect to x, we get the equation for the slope and deflection given below

$$\theta(x) = \int \frac{M(x)}{EI(x)} dx + c_1, \tag{5}$$

$$u_y(x) = \iint \frac{M(x)}{EI(x)} dx + c_1 x + c_2. \tag{6}$$

This simple formula hides considerable complexity since the denominator under the integral is piecewise constant (quite apart from the fact that the load itself may be a set of point loads so M_z will be piecewise linear).

2.1.1 | Implementation

The following steps are involved for calculating the slope and deflection for a stepped shaft using the direct/ piecewise integration method.

1. For each section of the beam, draw a separate free body diagram (FBD), and beginning from one end of the beam find the internal forces and moments at every cross-section.
2. Next, write a singularity function for the bending moment for each section of the beam and find the expressions for $\theta(x)$ and $y(x)$ (each may involve multiple concentrated or distributed loads and lead to a singularity function). This will lead to $N+1$ piecewise equations if there are N steps (each containing two constants of integration).
3. Match the slopes and deflections at each step, and the displacement boundary conditions at the two ends, resulting in $2N+2$ equations if there are N steps. These must be solved simultaneously.
4. Now, use these piecewise solutions to find the slope and deflection at points of interest.

2.1.2 | Pedagogical issues

This procedure is the most popular and basic method used for solving beam problems. Although this process is within the scope of the students, for stepped shaft problems with multiple steps and loads, it becomes a tedious and error-prone process as an FBD is drawn and forces and moments are computed for every cross-section. For even a straightforward problem in Figure 1, this method will lead to a 6 by 6 set of equations. The process must be repeated for every change in diameter so iteratively changing the diameters to verify the satisfaction of given slope or deflection constraints for bearings or gears will be impossible as students will be buried in an avalanche of computations.

2.2 | Castigliano's method

Castigliano's theorem states that the displacement $u(x_0)$ at any particular point x_0 on the shaft is equal to the first partial derivative of the complementary energy U in the body with respect to the force acting at that point in the direction of the displacement [26]. Similarly, the slope θ (x_0) of the shaft at any point on the shaft is equal to the first partial derivative of the complementary energy U in the body with respect to the concentrated moment/couple $C(x_0)$ acting at that point in the direction of the slope angle [26]. This is illustrated in Equation (7).

$$u(x_0) = \frac{\partial U}{\partial F(x_0)}, \theta(x_0) = \frac{\partial U}{\partial C(x_0)}. \tag{7}$$

2.2.1 | Implementation

To apply this method to the stepped shaft problem, the complementary energy U needs to be computed through integration over each section in symbolic form so that suitable derivatives can be computed [22]. A direct calculation will lead to the piecewise integral shown below in Equation (8).

$$U = \sum_{i=1}^{N} \int_{x_i}^{x_{i+1}} \frac{M(x)^2}{EI} dx. \tag{8}$$

Next, the energy U must be differentiated with respect to the force and moment at the point of interest, and the deflection and slope are obtained by substituting the numerical values for the external forces and moments. If there are no forces or moments at the point of interest, a fictitious force and/or moment must be applied, and the moment distribution must be computed with these additional fictitious forces, the energy U differentiated, and the value of the fictitious forces must be set to zero. This is a versatile approach, and several simplifications can be made to improve the efficiency (e.g., by differentiating the moment inside the integral sign to simplify the computation). It can also deal with complex curved beams and shear corrections as long the energy can be computed. However, it cannot be automated easily.

2.2.2 | Pedagogical issues

The procedure requires students to adopt an altogether new approach to solve the given problem, that is, a lot of class time is spent on teaching the basics of Castigliano's theorem and its applications. The use of fictitious forces and moments for finding deflections is quite hard to explain. If this is already part of the curriculum, then this approach could be feasible. The integrations can become increasingly complicated due to the squaring of the moment function. This is somewhat mitigated if the differentiation with respect to the force is computed before the integration (allowing for many terms to be dropped).

Even after performing these steps, this method only provides the deflection and slope at specific points of the shaft and not the overall deformed shape of the shaft. One needs to repeat the method at every point on the shaft to determine the deflection and slope, that is, every point must be resolved explicitly. If there is more than one point where forces/moments are not present, the moments must be computed again after adding new fictitious forces.

2.3 | Superposition method

If multiple external loads are acting along the length of the shaft, the procedure to calculate displacement and slope becomes quite long. However, because the governing equations are linear, the complex loading conditions can be modeled as a linear combination of simple loading configurations. As a result of this, the total deflection of the shaft is expressed as the algebraic sum of the deflection due to the individual loads. This method assumes that the deflection varies linearly with the load, and the initial geometry of the shaft does not change significantly due to the loads [13].

For example, if the transverse deflection due to loading configuration 1 is y_1 and deflection due to loading configuration 2 is y_2, then the total deflection, if both the loads are acting simultaneously on the shaft, is $y_1 + y_2$. Similarly, this method can be followed for determining the slope of the shaft. Many of the standard deflections and slopes can be found in various engineering handbooks and catalogs [24].

2.3.1 | Implementation

The following steps are involved for calculating the slope and deflection of a stepped shaft using the superposition method:

1. Divide the given loading configuration of the beam into standard loading configuration components.
2. Use the engineering handbook catalogs and tables to find the slope and deflection for each component of the beam loading.
3. Add the results of the components to find the total slope and displacement caused due to the various loads on the beam.

2.3.2 | Pedagogical issues

Although this method is extremely simple for the students to follow, its usefulness for stepped shafts is very limited since *geometries cannot be superposed—only external loads can*. This means that solutions must be available for each geometry under consideration—an impossible task. For solving step shaft problems, no catalog or table provide the deflection or slope formulae for stepped shafts. This is because no table/catalog can be made for all possible diameters of the stepped shafts. Thus, this approach becomes inapplicable for stepped shafts.

2.4 | Finite element method

The Finite Element Analysis (FEA) method subdivides a larger object into smaller elements and solves for equilibrium conditions at each node. Boundary conditions, such as fixtures, prescribed displacements or slope, and load are then applied to selected nodes on different elements. FEA software packages like ANSYS and ABAQUS are well equipped with all the tools to analyze complex mechanical components to determine stress, strain, displacement, and so forth. For most purposes, a computer application would be used to create a mesh subdividing the object and solve for the desired values. Hand-written equations could be used by utilizing methods, such as the Ritz or Galerkin methods, based on the weak formulation of a governing equation.

2.4.1 | Implementation

1. Select the suitable FEA software package for solving the given problem—typically SolidWorks or other solids modeling software (since students are unlikely to have already taken a course on the use of ANSYS or other FEA software packages).
2. Construct the beam/3D model of the stepped shaft. In SolidWorks, such beam models can be carried out using the "Weldments" feature.
3. Assign the required materials and appropriate boundary conditions (pin joint, roller joint, etc.), loads (point loads, distributed loads, moments) for the shaft.
4. Mesh the part and run the analysis.
5. Analyze and interpret the results to find the displacement and slope at the desired location.

2.4.2 | Pedagogical issues

Unless the students have already taken an FEA course, quite a bit of additional training is required before such a process can be meaningfully implemented. However, if the students are familiar with FEA, the approach allows for a general treatment of complex geometries. Changing cross-sectional geometries and trying again is possible if the students set up the initial geometry correctly. While this approach is by far the most versatile, it is not generally feasible because it requires expensive software, a good internet connection, and a reasonably good computer, making this approach unfeasible for many colleges around the world that do not have such capabilities. Furthermore, the approach is not suitable for exams since the setup time is too large. It may, however, be feasible for a project (in fact, we do use SolidWorks FEA for a project in the class).

3 | SINGULARITY FUNCTION APPROACH FOR SOLVING STEPPED SHAFT PROBLEMS AND ITS COMPUTER IMPLEMENTATION

Having described the current methods and their pedagogical issues, we now discuss the approach presented in this paper. It has been generally thought that it is not possible to use singularity functions for this task. We first draw the FBD of the shaft in question, shown in Figure 2. The shaft has a transverse force distribution represented by the function $p_y(x)$ and external couple distribution by $c_z(x)$—both treated as singularity functions. We will include the reaction forces and/or any reaction moments in the external load specification directly from the FBD. With these stipulations, the equations for $p_y(x)$ and $c_z(x)$ take the form

$$p_y(x) = R_1\langle x\rangle^{-1} + 0.75\langle x-35\rangle^{-1} + R_2\langle x-55\rangle^{-1} \quad \text{kN} - \text{mm}^{-1}, \tag{9}$$

$$c_z(x) = 0\text{kN} - \text{mm/mm}. \tag{10}$$

The above equations can be integrated since they simply require the use of singularity functions. From the FBD and integration, we get the following equations

$$R_1 = R_2 = -0.375 \ \text{kN}, \tag{11}$$

$$V(x) = -0.375\langle x\rangle^{0} + 0.75\langle x-35\rangle^{0} - 0.375\langle x-70\rangle^{0} \ \text{kN}, \tag{12}$$

$$M(x) = -0.375\langle x\rangle^{1} + 0.75\langle x-35\rangle^{1} - 0.375\langle x-70\rangle^{1} \ \text{kN} - \text{mm}. \tag{13}$$

EI is not a constant as *I* is a function of the cross-section area. We need to figure out how to integrate M_z/EI and obtain singularity function results. We begin by

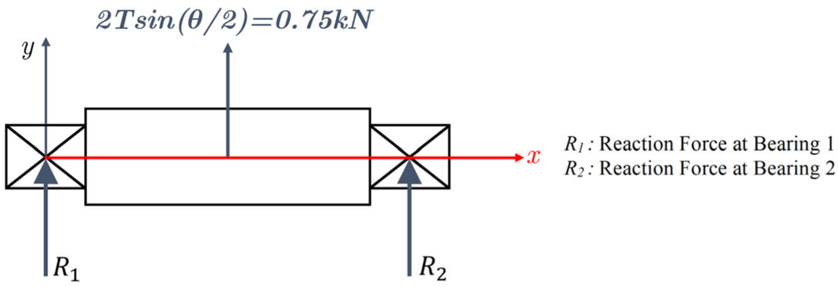

FIGURE 2 Free body diagram of the shaft in Figure 1 showing the external load.

defining *1/EI* as bending compliance. For the example problem under consideration

$$B(x) = 1/EI = \begin{cases} 6.37\times10^{-7} & \text{if} \quad x < 15 \\ 4.35\times10^{-7} & \text{if} \quad 15 < x < 55 \\ 6.37\times10^{-7} & \text{if} \quad 55 < x < 70 \end{cases} (\mathrm{kN}-\mathrm{mm}^2)^{-1}. \tag{14}$$

In general, we note that for stepped shafts $B(x)$ itself can be written as a sum of simple Heaviside step functions of the form

$$B(x) = \sum \Delta B_i \langle x - b_i\rangle^0. \tag{15}$$

For our specific example,

$$B(x) = \left(6.37\langle x\rangle^0 - 2.02\langle x-15\rangle^0 + 2.02\langle x-55\rangle^0\right) \times 10^{-7}(\mathrm{kN}-\mathrm{mm}^2)^{-1}, \tag{16}$$

For evaluating $\int B(x)M(x)dx$, we are required to integrate the product of some function $M(x)$ and a Heaviside function. This is done by

$$I = \int_{-\infty}^{x} f(x)\langle x-a\rangle^0 dx = \begin{cases} 0 & if \quad x < a \\ \int_{-\infty}^{x} f(x) \quad dx - \int_{-\infty}^{a} f(x) \quad dx & \text{otherwise} \end{cases}. \tag{17}$$

The above can be conveniently written as

$$I = (g(x) - g(a))\langle x-a\rangle^0, \text{where} \quad g(x) = \int_{-\infty}^{x} f(x) \quad dx. \tag{18}$$

To use the above expression, we now introduce $Q(x)$ and $P(x)$

$$Q(x) = \int_{-\infty}^{x} M(x) \quad dx = -0.1875\langle x\rangle^2 + 0.375\langle x-35\rangle^2 - 0.1875\langle x-70\rangle^2, \tag{19}$$

$$P(x) = \int_{-\infty}^{x} Q(x)dx = -0.0625\langle x\rangle^3 + 0.125\langle x-35\rangle^3 - 0.0625\langle x-70\rangle^3, \tag{20}$$

which are simply integrals of singularity functions that we would anyway use for computing slopes and angle for constant diameter shafts. If *EI* was constant, the slope and deflection are simply obtained by dividing the above results by *EI* and adding the proper constants of integration. However, for nonconstant *EI* we need to proceed differently. By using the above result in Equation (3) and after slightly regrouping terms we get the following remarkable result

$$\theta(x) = Q(x)B(x) - \sum Q(b_i)\Delta B_i\langle x-b_i\rangle^0 + a_1, \tag{21}$$

$$\theta(x) = Q(x)B(x) - 8.29\times10^{-6}\langle x-15\rangle^0 + 8.02\times10^{-5}\langle x-55\rangle^0 + a_1, \tag{22}$$

where $Q(x)$ and $B(x)$ are defined respectively by Equations (19) and (16).

In other words, we get an explicit expression for the rotation angle in terms of singular functions that can be easily evaluated. Moreover, the result is in the form of a "correction" to the constant cross-section beam problem and can be explained as such to students. Integrating Equation (22) again, we obtain an explicit solution for the displacement as

$$u(x) = P(x)B(x) - \sum Q(b_i)\Delta B_i\langle x-b_i\rangle^1 + a_1 + \sum P(b_i)\Delta B_i\langle x-b_i\rangle^0 + a_1 x + a_2, \tag{23}$$

$$u(x) = P(x)B(x) - 8.29\times10^{-6}\langle x-15\rangle^1 + 8.02\times10^{-5}\langle x-55\rangle^1 - 4.25 \times 10^{-5}\langle x-15\rangle^0 + 1.90\times10^{-3}\langle x-55\rangle^0 + a_1 x + a_2. \tag{24}$$

We have thus obtained explicit expressions for stepped shaft slopes and deflections without the need for either Castigliano's theorem or numerical discretization. Furthermore, these have been directly implemented in an Excel spreadsheet (see Figure 5) for the case of simply supported shafts on bearing as an explicit solution. This is made possible by the fact that a step function is simply $(x > a)$ in Excel so that any singularity function can be implemented in Excel using $(x–a)^n * (x > a)$ and the graphs can be plotted.

4 | ASSESSMENT OF THE EXCEL-BASED APPROACH AND ITS

4.1 | Example homework problem

Students are introduced to singularity functions in lectures and then given homework assignments for simple beams with simple loading, fixtures, and constant cross-sectional area. Problems such as these can be found in Shigley's Chapter 4 [26].

The shafts with single-step are introduced in lectures, and a homework problem is given to the students for them to practice how to carry out the steps listed in the singularity function-based solutions and to gain a deeper understanding of the organization of the Excel spreadsheet. After this exercise, an Excel spreadsheet is provided to the students to select the material, geometry, bearing locations, load location, magnitude, and direction. This Excel sheet uses a solver built-in Visual Basic for Applications (VBA) to create plots for the shear forces, bending moment, slope, and deflection along the shaft. The students are then responsible for determining if the design is satisfactory or if any design changes are needed. If changes are needed, they are then tasked with redesigning the shaft in a reasonable way and explaining how they did so. This allows students to move past the detailed equations and algebra and instead answer high-level design questions. The solver is also not a black box because they understand the equations and mathematical steps from previous lectures and homework assignments.

A sample problem assigned in the Fall 2020 semester is as follows. The problem is originally taken from Shigley's [26]. The problem statement also includes a step-by-step plan to guide the students.

4.1.1 | Problem statement from Fall 2020

Consider the shaft shown in Figure 3. An AISI 1020 cold-drawn steel shaft with the geometry shown in Figure 3 carries a transverse load of 7 kN and a torque of 107 N m. Assuming a root radius of 3 mm at all steps, analyze the shaft to determine the fatigue life of the shaft. Verify whether the shaft has infinite life or not.

4.1.1.1 | *Analysis*

Notice that the stiffness of the shaft is not examined in this version since *it is not possible to compute the stiffness and iteratively adjust it until it is satisfactory*. On the other hand, the strength calculations are relatively simple and require nothing more than some pre-existing formulae. There is little, if any, design content in this formulation.

4.1.2 | New problem statement with the use of Excel

The following problem involves a full design calculation: Choose some dimensions for the shaft and then check for stiffness. For this, I require you to use the shaft deflection spreadsheet to check if all the diameters are satisfactory. All units are in millimeters.

"An AISI 1020 cold-drawn steel shaft with the geometry shown in Figure 3 carries a transverse load of 7 kN and a torque of 107 N m. Examine the shaft for strength and deflection. If the largest allowable slope at the bearings is 0.001 rad and at the gear, the mesh is 0.0005 rad, what is the factor of safety guarding against damaging distortion? If the shaft turns out to be unsatisfactory, what would you recommend to correct the problem?"

4.1.2.2 | *Features that improve the quality of engineering education*

In this case, the students have to evaluate the stiffness and make adjustments to the shaft diameter until the required deflection and slope conditions are met. This is a challenging problem (made possible with the Excel spreadsheet) and requires students to show judgment,

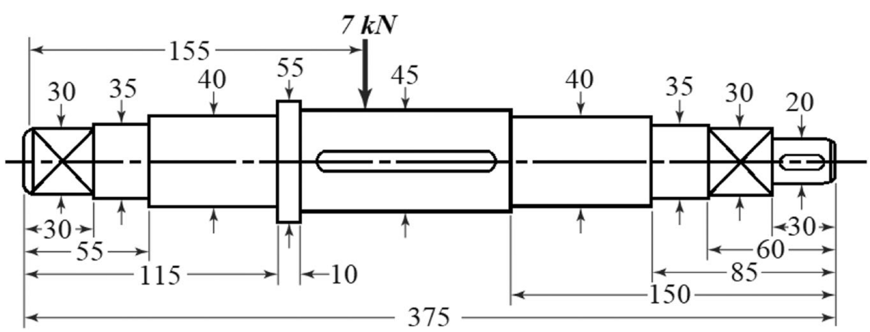

FIGURE 3 Sample stepped shaft problem from the course homework.

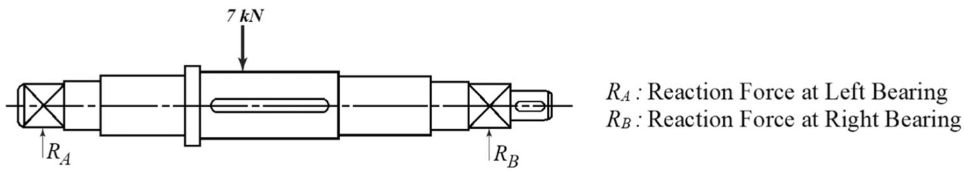

FIGURE 4 FBD of the shaft is shown in Figure 3. FBD, Free Body Diagram.

including exploring which diameters matter, which diameters have the most impact on the deflection and slope criteria, and how much one can change the different diameters but still retain the same design configuration. This allows students to move from the current focus on laborious arithmetic focused on the lower levels of Blmmos taxonomy (i.e., "apply") to higher levels of blooms taxonomy, ("analyze and judge").

4.1.2.3 | *Strategy*

1. Draw FBDs for the front and side view to find out what external forces are acting on the shaft. You do not have to find the reaction forces; Excel will do it for you.
2. Go to the shaft deflection spreadsheet and determine if the dimensions are ok or not, that is, do a stepped shaft problem (look at the allowable deflections for the spur gear and regular ball bearings and see if they are acceptable).
3. If the shaft's slope or deflection is too high at critical locations, redesign the shaft.
4. Calculate the Factor of Safety (FOS) of the slope and deflection at all critical locations.

Step 1: *Free Body Diagram*—The FBD of the AISI 1020 cold-drawn steel shaft shown in Figure 3 is illustrated in Figure 4.

Note: R_A and R_B are the reaction forces from the bearings. FBD, Free Body Diagram.

Step 2: *Spreadsheet*—Given the problem statement and information in Figure 3, the inputs are entered into the spreadsheet as shown in Figure 5. These inputs include the elastic modulus (E), the shaft's overall length (L), location of steps and diameter, bearing locations, and external forces. These inputs are highlighted in the spreadsheet using orange color. Once the input values are entered, the Excel spreadsheet solver generates four plots: Shear force, Bending moment, Slope, and Deflection (see Figure 6). The values of the deflection and slopes at the bearings and the point of force application are given in Table 2.

Step 3: *Iterative Design*—Because the slope at both bearing locations is greater than 0.001 rad, the shaft needs to be redesigned to increase stiffness. This part of the assignment is open-ended, and students need to find a reasonable solution by iterating and evaluating the shaft diameter and step locations. Students would show a final shaft design and provide justifications for the changes they made.

Step 4: *Factor of Safety*—The last part of the assignment involves calculating the factor of safety for the deflection and slope. This is done to indicate if the selected changes to the shaft have improved the design and meet the requirements listed in the problem statement.

4.2 | Self-efficacy assessments, results, and discussion

After the homework problem, surveys were conducted to assess student self-efficacy in the following categories:

1. Can the student's defeature (remove some grooves and steps) a shaft sufficiently to focus on important features? This is an important goal for the class since defeaturing a solid model to remove features that are not important but may cause meshing complications is an essential step in using FEA also.
2. Can they convert the loads and steps into symbolic versions to be used in Excel?
3. Can they identify how the geometrical parameters affect the deflections and slopes?
4. Can they redesign the shaft (by making suitable changes) to meet the stiffness goals?

As can be seen from the self-efficacy surveys in Figure 7, students were not comfortable defeaturing the shaft. Based on common questions asked during the office hours and lectures, it was evident that students had difficulty understanding what steps and grooves were critical to the analysis. Also, based on the student's solutions, they favored keeping as many features as possible and did not feel comfortable generalizing the shaft. This clearly pointed to the difficulty that students had in qualitative analysis of the deflection features. Despite this, students otherwise felt confident with other aspects of the problem.

The Excel spreadsheet allows the students and instructors to explore the differences in the deflection made by

	A	B	C	D	E	F	G	H	I	J	K
1	Shear Force, Bending Moment, Slope and Deflection for Stepped Shafts										
2											
3	CHOOSE UNITS FIRST		UNITS		SI						
4											
5											
6		MATERIAL PROPS									
7											
8	CHOOSE MODULUS	Designer	Elastic Modulus	2.10E+05	MPa(N/mm^2)						
9											
10			GEOMETRY								
11											
12	Choose Shaft length	Designer	Length	3.75E+02	mm						
13											
14					mm						
15					mm						
16			number of steps	6		WARNING: THIS IS ALWAYS ONE MORE THAN THE # OF SHOULDERS					
17	SHAFT STEPS	DESIGNER	STEP #	@(mm)	Dia(mm)	EI(Nmm^2)	1/EI	D(1/EI)			
18	THIS IS THE BEGINNING OF THE SHAFT, DON'T MESS WITH THIS		0	0.00E+00	3.00E+01	8.35E+09	1.20E-10	1.20E-10			
19			1	5.00E+01	4.00E+01	2.64E+10	3.79E-11	-8.19E-11			
20			2	1.15E+02	5.50E+01	9.43E+10	1.06E-11	-2.73E-11			
21			3	1.25E+02	4.50E+01	4.23E+10	2.37E-11	1.31E-11			
22			4	2.25E+02	4.00E+01	2.64E+10	3.79E-11	1.42E-11			
23			5	2.90E+02	3.00E+01	8.35E+09	1.20E-10	8.19E-11			
24			6			0.00E+00	0.00E+00	-1.20E-10			
25			7			0.00E+00	0.00E+00	0.00E+00			
26											
27			LOADS In the x-Y and X-Z planes								
28											
29	TRANSVERSE LOADS	DESIGNER	Load #	@(mm)	Y Value (N)	Z Value (N)		Vtot(N)	Mtot(Nmm)	Θ_tot(rad)	d_tot(mm)
30			1	1.55E+02	-7.00E+03	0.00E+00		3.89E+03	5.44E+05	1.67E-04	1.25E-01
31			2					0.00E+00	0.00E+00	0.00E+00	0.00E+00
32			3					0.00E+00	0.00E+00	0.00E+00	0.00E+00
33			4					0.00E+00	0.00E+00	0.00E+00	0.00E+00
34			5					0.00E+00	0.00E+00	0.00E+00	0.00E+00
35			6					0.00E+00	0.00E+00	0.00E+00	0.00E+00
36			7					0.00E+00	0.00E+00	0.00E+00	0.00E+00
37			8					0.00E+00	0.00E+00	0.00E+00	0.00E+00
38			9					0.00E+00	0.00E+00	0.00E+00	0.00E+00
39			10					0.00E+00	0.00E+00	0.00E+00	0.00E+00
40			11					0.00E+00	0.00E+00	0.00E+00	0.00E+00
41	Locate Bearings	Designer	Bearing 1 locations	15	3.89E+03	0	<-Bearing Load 1	0.00E+00	0.00E+00	1.49E-03	0.00E+00
42			Bearing 2 location	330	3.11E+03	0	<-Bearing Load 2	3.11E+03	0.00E+00	1.41E-03	1.39E-17
43											

FIGURE 5 Excel-based solution to the sample shaft problem in Figure 3.

removing different features and thus gain some understanding of the effects of features on the deflections.

To gain an objective measure of student performance to supplement the self-efficacy surveys, a stepped shaft design problem was included in the final exam, and the results were evaluated. We emphasize that without the use of singularity function and Excel, it had hitherto been impossible to include such a problem in a final exam. Furthermore, evaluating students' solutions is easy with the Excel spreadsheet. On the other hand, even with FEA software, due to the issues with meshing and assigning boundary conditions, it would be impossible to carry out the complete FEA on the shaft within the time constraints of an exam.

4.2.1 | Typical homework problem that was asked previously (Fall 2019)

For this homework problem, students were asked to determine the loading, slope, and displacements for a stepped shaft. The problem consisted of two parts. For the first part, the students were instructed to perform the calculations by hand.

Part 1: "The following stepped shaft is made of AISI 1020 CD steel. We want to determine slopes and displacements for this shaft. Assume the shaft is circular, all dimensions are in millimeters and $F = 10\,\text{kN}$), determine the following:

(a) Draw a free-body diagram of the beam shown.
(b) Determine the loading equation.
(c) Determine the slope and elastic curve for the stepped shaft."

Features that improve the quality of engineering education: The typical amount of time spent on the first part of the homework ranged between 3 and 4 h, with some students reporting up to 6 h spent on the problem. For the second part of the homework assignment, the students were asked to use Excel to perform the calculations.

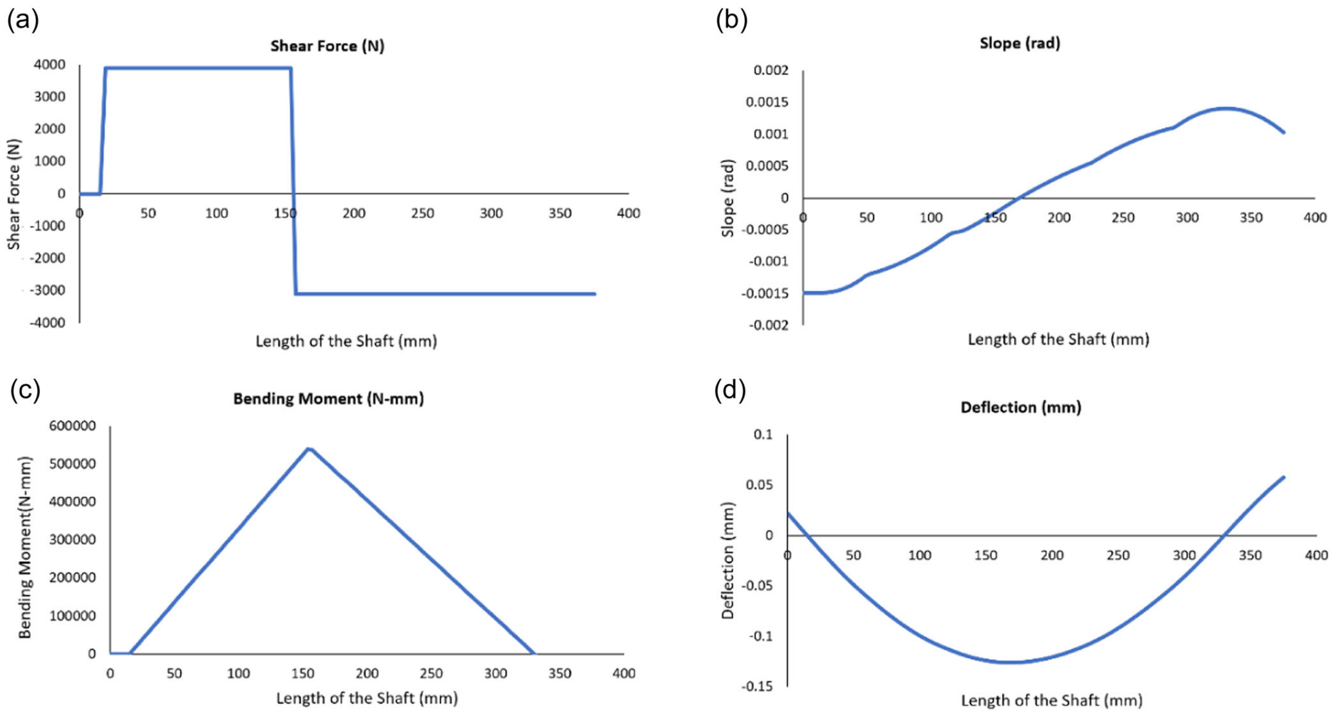

FIGURE 6 Result plots generated by the Excel spreadsheet solver. Here, (a) shear force diagram; (b) slope diagram; (c) bending moment diagram; (d) deflection diagram.

TABLE 2 Values for the shaft deflection and slope at locations of the bearings and gears.

Location	15 mm	155 mm	330 mm
Slope (rad)	-1.49×10^{-3}	1.67×10^{-4}	1.41×10^{-3}
Deflection (mm)	0	−0.125	1.39×10^{-17}

Part 2: "The following beam is made of 1018 CD steel. You are tasked to design the dimensions for the shaft shown below. The load $F = 8$ kN, the dimensions for the bearings, the overall length of the shaft, and the point of load applications are fixed. The diameters $d1$ and $d2$ and the lengths $L1$ and $L2$ are design parameters that you must determine. It is suggested that you input parameters for the diameters and lengths into the Excel spreadsheet provided then iterate until you get satisfactory dimensions. Deflections must satisfy the suggested minimums for spherical ball bearings and spur gears with $p < 10$ (Gear is located at the point where F is applied). All dimensions are in millimeters."

Features that improve the quality of engineering education: Students reported average times of 20–40 min on this part of the problem with one student reporting a maximum time of 90 min.

4.2.2 | Typical exam problem that was asked previously (Fall 2019)

For the shaft shown in Figure 8, $D1 = 30$ mm, $D2 = 40$ mm, $D3 = 50$ mm, and $r = 5$ mm. It rotates at 600 RPM for 8 h a day and carries a transverse load of 6 kN and torque of 2×10^5 N-mm. Will it be safe for infinite life if not, what is the expected life of the shaft? Which is the critical section where fatigue failure may occur?

4.2.2.4 | *Analysis*

Here, too, questions about deflection cannot be considered for real shafts due to the number of steps in the shaft. Due to the tedious table lookups involved with empirical formulae for fatigue, design iterations are ruled out even for the strength calculation. So, the focus of the exam was only on verifying an existing design with some judgment involving where the critical sections could be.

4.2.3 | Revised problem statement using the Excel-based approach

The shaft shown below in Figure 8 rotates at 600 RPM for 8 h a day and carries a transverse load of 6 kN and torque of 2×10^5 N-mm. There are cylindrical roller bearings at the

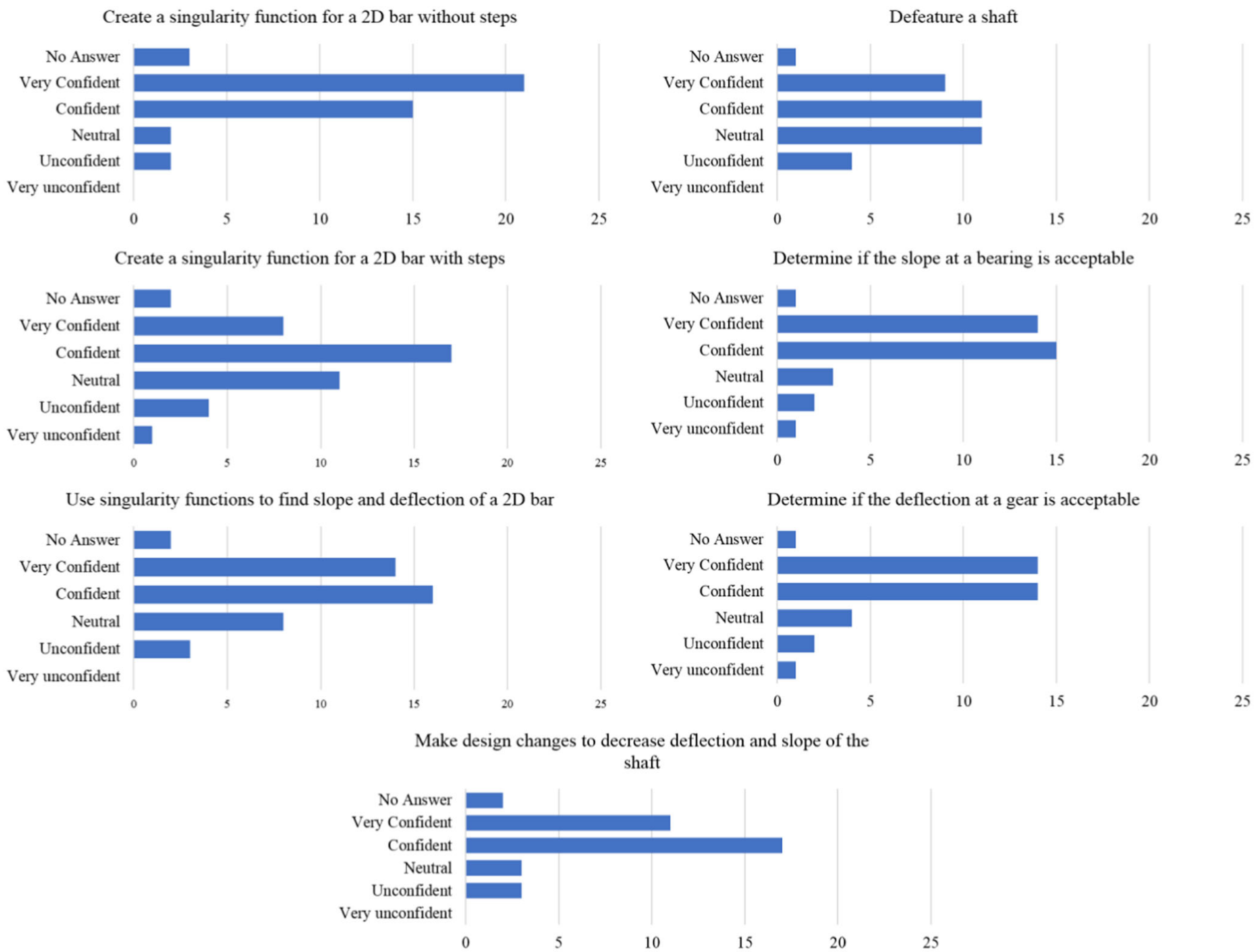

FIGURE 7 Student self-efficacy survey results. About 200 students from the class were surveyed to analyze the effectiveness of the Excel-based method.

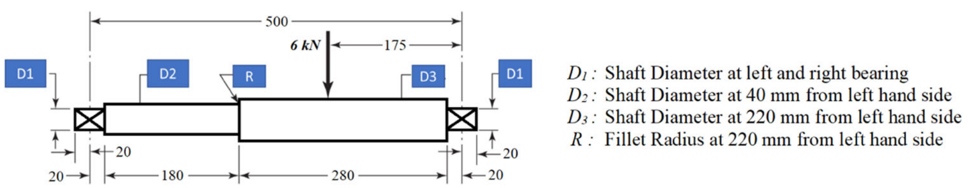

FIGURE 8 Final exam problem. Students had about 45 min to use the Excel-based shaft analysis to carry out an iterative design and fatigue analysis of this shaft.

two ends, and the spur gear (which is located at the point of application of the load) can withstand a slope of only 0.0005 radians. Find suitable shaft dimensions (*D*1, *D*2, *D*3, and fillet radius *R*) so that (a) the deflections are within limits and (b) the shaft lasts at least 10 years with a factor of safety of 2. Assume that the shaft is made up of AISI 1040 CD steel. This is an open-ended problem, therefore make some sensible design decisions and explain your assumptions well. I will evaluate your justifications. All dimensions shown in the Figure are in mm.

Note: Part B is found by fatigue calculations using its own Excel calculator; this will not be explored in this paper.

4.2.3.5 | *Features that improve the quality of engineering education*

We are now able to ask an open-ended and complete design solution in about 1 h during an exam. Also, since the calculations are done in Excel. The results are easily verifiable by the TA/Instructor by simply entering the same numbers and checking if the solution is suitable.

Students' work on the homework problem and their work in the exam were evaluated based on three categories: (a) How accurate were the students in specifying the inputs (forces and shaft steps); (b) How well did they interpret the results; and (c) How well did they carry out the redesign. Inputs refer to taking the information from the problem statement or figures and entering it into the spreadsheet correctly. Interpreting results includes finding the values of the deflection and slope at critical locations and evaluating if the shaft design meets the requirements. Lastly, redesigning the shaft was graded based on if they could create a design that met the requirements of the bearing and gear but did not do so with an excessive factor of safety. The correct column indicates that students received full points for the specified task, and error means that they made some mistake that resulted in a point deduction (see Figures 9 and 10). An error could be as severe as not attempting that part of the problem or having a slightly large shaft for the final design.

In terms of designing the shaft, there are three major parts inputs, interpreting results, and redesigning. Figures 9 and 10 show that students make more input errors on the final exam when compared to the homework assignment. This is most likely due to the pressure of a timed exam and students not taking the time to double-check all the inputs. Generally, students were able to accurately interpret the results, but fewer were able to make reasonable design changes.

A careful look at the results suggests that most of these errors were due to over-designing the shaft—making the diameters much larger, in many cases, making them 50 cm in diameter, which is unrealistically large for the problem at hand. This indicates that students need help understanding the tradeoffs between cost and size of parts versus a factor of safety; if a factor of safety of 2 is required, it is not necessarily better to design for a factor of safety of 10. A further aspect revealed from the iterations carried out by the students is that they have difficulty with estimating the sizes (in some cases, starting with an initial shaft diameter of 5 mm, not realizing that such a dimension would make it wire).

The course evaluations and student comments indicated that students were very appreciative of the approach taken where the decision-making and reasoning were emphasized, over-focusing just on calculations. Even students who did not perform well in the class indicated that they valued the class. This was made possible by using Excel and singularity functions to provide students with a realistic component design experience.

5 | ADVANTAGES AND DISADVANTAGES OF THE USE OF EXCEL

(1) The overall average time to solve stepped shaft design problems using MS Excel VBA reduces by approximately 75% as compared to the traditional methods (discussed in Section 2) of solving it. We note such stepped shaft problems are actually treated as a whole case study and broken up into multiple subproblems spanning the whole semester, by Budynas and Nesbitt [26].They state on page 3671 of the 8th edition and page 391 in the 11th (most recent) edition that the deflection analysis is "… lengthy and tedious to carry out manually, particularly for multiple points of interest." They go on to add that "any general-purpose finite element software can readily handle any shaft problems. Special-purpose software solutions for 3-D shaft analysis are available but somewhat expensive.…" They then proceed to do a deflection analysis as a case study by using suitable software but provide no details.
(2) The Excel VBA program provides a very simple interface to the students eliminating the need of learning advanced programming skills.

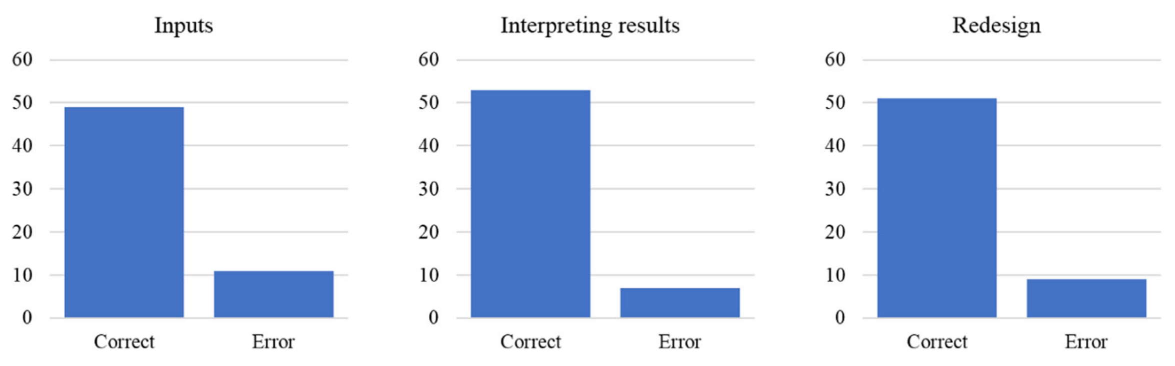

FIGURE 9 Completely correct versus error in work for different grading criteria on homework problems. The correct column indicates that students received full points for the specified task, and error means that they made some mistake that resulted in a point deduction.

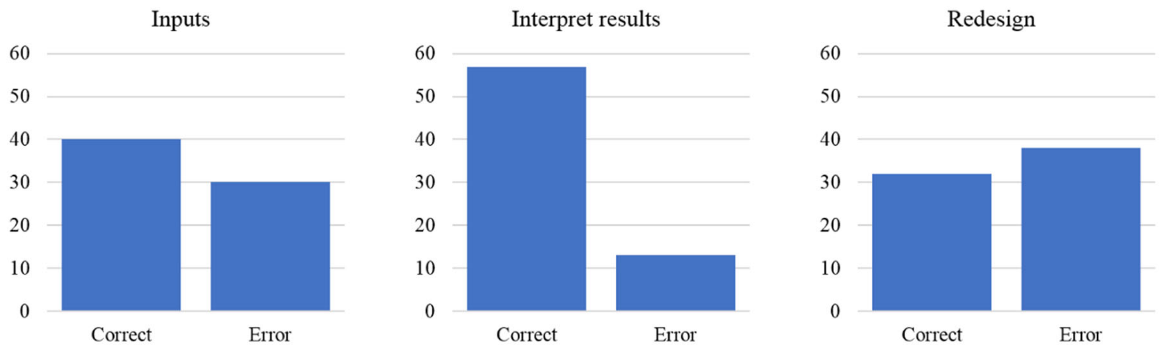

FIGURE 10 Completely correct versus error in work for different grading criteria on the final exam. Problem. The correct column indicates that students received full points for the specified task, and error means that they made some mistake that resulted in a point deduction.

(3) The dynamic nature of the result plots provides the students with an easier way of making necessary design changes and visualizing them.
(4) Rather than focusing on tedious arithmetic, students were able to focus on design decision-making, interpret the results, and move to higher levels of Bloom's taxonomy.
(5) The use of Excel allows the students to focus on the concepts of the problems and the effect of different parameters on the final results. A full iterative design is not possible unless it is assigned as a team project. In contrast, with the use of this Excel software, the total time required by the students to complete the whole task is reduced to 20 min or less in an exam.
(6) One of the principal disadvantages of using Excel was that students tended to quickly use it as a black box. We were able to mitigate this effect somewhat by asking students to do one homework with a shaft with one shoulder so that they can learn the process.
(7) A second disadvantage was that not all faculty were comfortable with the Excel-based design approach since they were not very familiar with Excel VBA. We are planning a short course on Excel VBA for engineers for both students and interested faculty to mitigate this.

6 | CONCLUSION

This paper addresses the difficulty of teaching the design of stepped shafts, which is one of the core problems in the design of machine elements. The main challenge, which prevents instructors from teaching students to carry out an iterative design approach is the extensive algebra and calculus needed for hand calculation and the nonavailability of a simple approach for computational solutions. We have demonstrated an approach, using singularity functions and Excel, to solve stepped shaft problems quickly. Transparently and intuitively. This allows students the opportunity to use their engineering knowledge and intuition to obtain solutions to design problems. This technique allows students to improve their skills in engineering design and practice without the time devoted to time-consuming algebra. We have demonstrated the effectiveness of this technique from the courses in which this methodology was implemented

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CONFLICT OF INTEREST

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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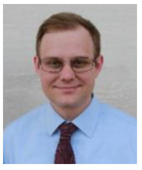

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APPENDIX A: Excel VBA Code

The code below shows the two major functions needed for the Excel-based solution:

A1: VBA function to integrate singularity functions as many times are needed

```
Public Function SingularIntegrate(x As Double, StartRange As Range, CoeffRange As Range, times As Integer) As Double
Application.Volatile True
Dim WF As WorksheetFunction
Set WF = Application.WorksheetFunction
SingularIntegrate = 0
nsteps = StartRange.Rows.Count
For ii = 1 To nsteps
xa = x StartRange.Cells(ii, 1).Value
ci = CoeffRange.Cells(ii, 1).Value
jj = times 1
If (xa > 0) And jj >= 0 Then
SingularIntegrate = SingularIntegrate + ci * WF.Power(xa, jj)/WF.Fact(jj)
End If
Next ii
End Function
```

A2: Integrating the product of the Beam compliance step function and the Moment function and its integrals

```
Public Function BeamGeom(x As Double, StartRange As Range, CoeffRange1 As Range, CoeffRange2 As Range, inType As Integer) As Double
Application.Volatile True
Dim WF As WorksheetFunction
Set WF = Application.WorksheetFunction
L = Range("D12").Value
myPi = 3.141592
Dim nsteps As Integer
nsteps = Range("D16").Value
Dim a As Double
BeamGeom = 0
n = 17
m = 0
Do Until m = nsteps
n = n + 1
m = m + 1
a = Range("D" & n).Value
EI_Inv = Range("H" & n).Value
xa = x a
If xa > 0 Then
BeamGeom = BeamGeom + EI_Inv * (SingularIntegrate(x, StartRange, CoeffRange1, inType + 2) SingularIntegrate(a, StartRange, CoeffRange1, inType + 2) SingularIntegrate(x, StartRange, CoeffRange2, inType + 1) + SingularIntegrate(a, StartRange, CoeffRange2, inType + 1))
If inType > 1 Then
BeamGeom = BeamGeom EI_Inv * (SingularIntegrate(a, StartRange, CoeffRange1, 3) SingularIntegrate(a, StartRange, CoeffRange2, 2)) * xa
End If
End If
Loop
'BeamGeom = Range("D" & 30).Value
If x > L Then
BeamGeom = 0
End If
End Function
```

APPENDIX B: Student Self-Efficacy Questionnaire

We developed a questionnaire based on a Likert scale consisting of the following questions to quantify student self-efficacy in designing stepped shafts:

For the following questions use the five-point scale below

1. Very confident
2. Confident
3. Neutral
4. Not very confident
5. Not confident at all

1. Creating a singularity function for a 2D bar without steps
2. Creating a singularity function for a 2D bar with steps
3. Defeaturing a shaft
4. Verifying if the slope at the bearings is within acceptable limits
5. Verifying if the deflections at gears are within acceptable limits
6. Iteratively changing dimensions to decrease the slope and deflection of the shaft