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BYOE: Experimental Demonstration of Simplifying a System of Parallel Forces

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Abstract:
The purpose of this Bring Your Own Experiment (BYOE) session is to describe a low-cost and hands-on activity of simplifying systems of parallel forces for the engineering mechanics (Statics) course. One of the most fundamental concepts in Statics is to reduce a system of forces to a force-couple system. As a hands-on activity can reinforce a fundamental concept, a demonstration unit was prepared using digital weight scales, a clear acrylic sheet, weights, and leveling feet. Once the concept of simplifying a system of parallel forces was covered, multiple demonstration units were given to different groups of students to perform a task along with instructions.

Introduction:
Statics is the most fundamental engineering mechanics course for different engineering programs including Aerospace, Civil, Biomechanical, and Mechanical Engineering [1-3]. Various efforts have been made to enhance the understanding and visualization of fundamental concepts in engineering mechanics by demonstrating different types of physical tools in classroom setups. [4-7]. However, developing such tools takes lot of works. Oftentimes, the instructor has to rely on the tools that are readily available on the market or improvise and it presents challenges in terms of time commitment and costs. The demonstration unit outlined in this paper addresses these challenges. The author constructed a laboratory scale model of a textbook exercise problem to demonstrate a system of parallel forces. It is engineered to be low-cost, compact, and portable. Any instructor can easily replicate the same unit using readily available materials or similar alternatives. By making it accessible and affordable, the demonstration unit facilitates effective teaching and learning of the concepts across different educational environments.

When a structure is subjected to experiencing a system of forces, it is more convenient to reduce the system of forces into a single resultant force and moment acting on a point for static analysis. This reduction of the system of forces is known as an equivalent force-couple system. The initial step in structural analysis under combined loads involves establishing an equivalent force-couple system.
A system of forces can be parallel forces that can have parallel lines of action with an equal or opposite sense. When a system of parallel forces acts on a body, it is often required to find the magnitude and direction of the resultant force and its point of application.

Assuming the forces $F_1, F_2, and\ F_3$ are parallel to y-axis in Figure 1. The resultant $\boldsymbol{R}$ will also be parallel to y-axis. As the moment of a force about a point must be perpendicular to that force, the moment of all three forces and the moment of resultant about the origin are confined to the xz plane. The position vector, r, defines the point of application of the resultant force $\boldsymbol{R}$.

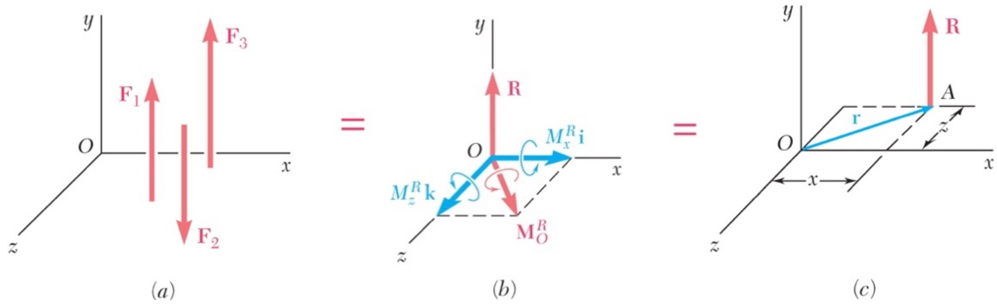

Figure 1: (a) Parallel system of forces (b) equivalent force-couple system at origin O, and (c) resultant force and its point of application [8]

Implementation of the Concept in the Classroom:

Two exercise problems (Figures 2 and 3) from the textbook are initially solved in the classroom on the topic of reducing a system of parallel force. Once the problems are solved, a demonstration unit (figure 4) representing a similar concept is given to the students. Students were asked to find out the resultant force and its point of application. The author chose to reconstruct these particular textbook problems to identify the level of conceptual understanding of equivalent force-couple systems, coordinate systems and vector cross-products by the students.

Textbook exercise problem 1:

A square foundation mat supports the four columns shown below. Determine the magnitude and point of application of the resultant of the four loads.

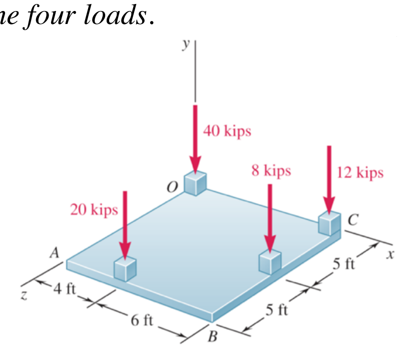

Figure 2: Textbook exercise problem [8]

Textbook exercise problem 2:

Three children are standing on a 5×5 m *raft. If the weights of the children at point A, B, and C are 375 N, 260 N, and 400 N, respectively, determine the magnitude and the point of application of the resultant of three weights.*

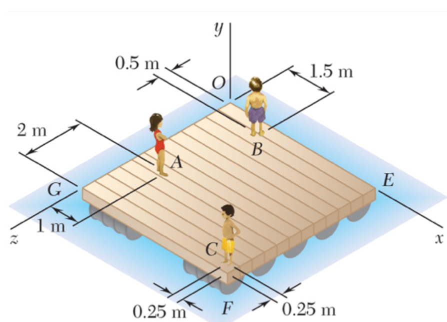

Figure 3: Textbook exercise problem [8]

Demonstration Unit

A single unit consists of a rectangular-shaped clear acrylic, three digital weight scales, three leveling feet, wights, markers, and measuring tapes. Figure 4 shows the tools required for a single demonstration unit. Table 1 also shows the list of items. A brief explanation of the experimental procedure is explained below.

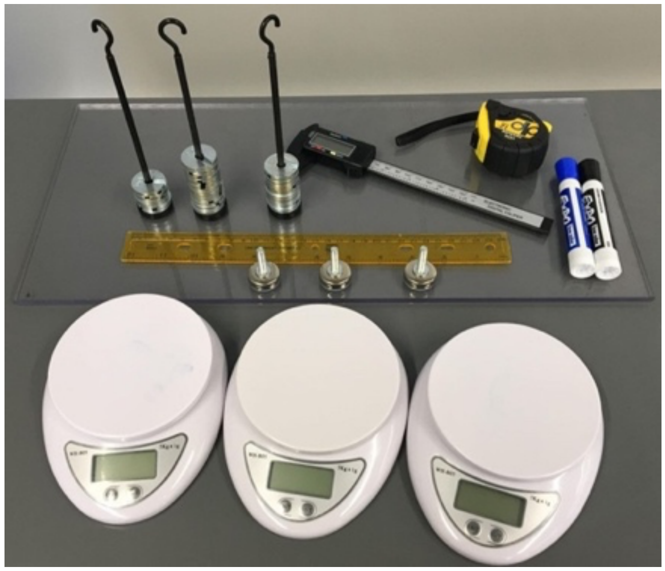

Figure 4: Tools for a single demonstration unit

Table 1: A list of Materials for the demonstration unit

#	Item	Notes
1	Weights and weight hangers	These are purchased from www.tecquipment.com. The weights are 10g each. These parts can also be replaced by any other weights and hangers.
2	Digital kitchen scale	LuckyStone Wh-B05 Electronic Digital Kitchen Food Scale (www.amazon.com). This scale is capable of measuring up to 5kg with 1g resolution.
3	Leveling feet	These are purchased from www.mcmaster.com.
4	Acrylic	Purchased locally
5	Tape measure	
6	Slide calipers	
7	Ruler	
8	Marker	

Experimental Procedure:

Initially, the measuring scales are arranged at a reasonable distance from each other on the table and three leveling feet are placed on top of them. The clear acrylic is then carefully placed on top of the three leveling feet (Fig.5a). There are no predefined distances between the leveling feet as long as the acrylic is balanced properly. The readings on the measuring scale are zeroed. The weight of the leveling feet and the clear acrylic are not considered. The top faces of the leveling feet are visible through the acrylic sheet. A marker is used to mark the points on top of the acrylic sheet where the top of the leveling feet is visible (Fig. 5b).

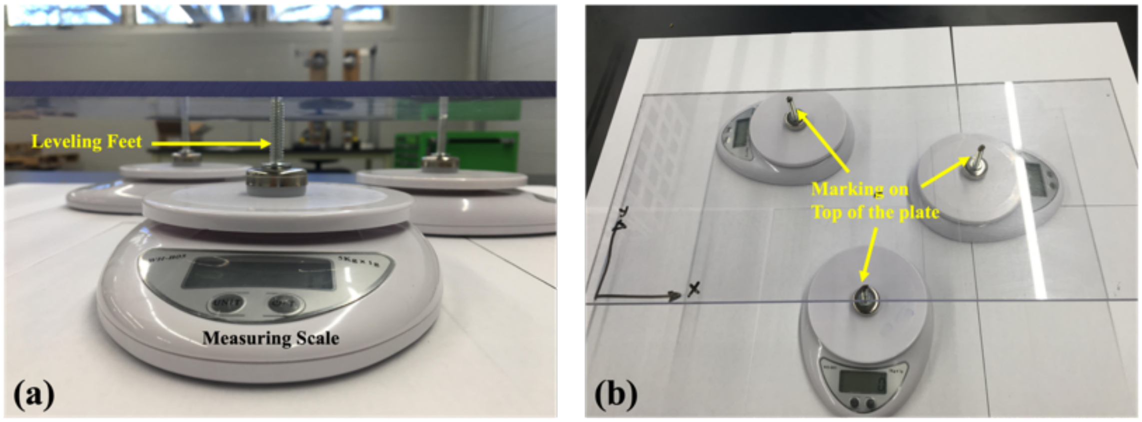

Figure 5: Acrylic on top of the leveling feet and measuring scale.

The points can be given names as A, B, and C or 1, 2, and 3. Three weight hangers are taken, and different numbers of masses are added to them. Three masses can be equal or different. For this demonstration, different masses are chosen. Three weight hangers with different masses are laid on top of the points marked on the acrylic (Fig. 6).

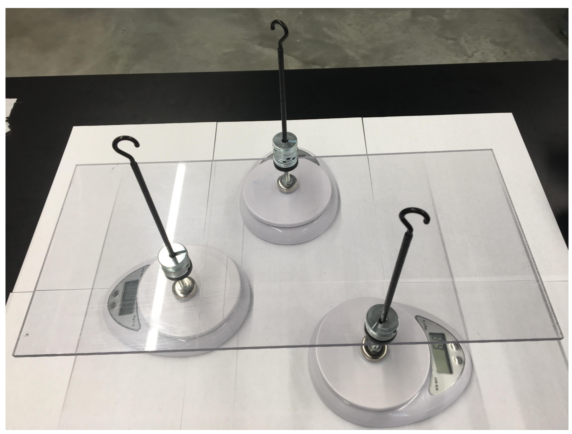

Figure 6: Weight hangers with different loads on top of the acrylic

Careful observation is required to place the weight hangers at the midpoint. At this stage, the readings on the measuring scales are noted. Each scale should show the same mass as placed on top of them. The digital scale shows the reading in terms of grams but later converted to force. Students may choose to keep the reading in grams throughout the calculation and later convert into force at the end. After taking notes of the scale readings, the weight hangers are carefully removed. A ruler scale, measuring tape, or slide calipers were used to measure the coordinates of three different points where the loads were placed. A careful observation is required while measuring the coordinates of the points so that the acrylic does not move. Students may choose to move the acrylic carefully from the leveling feet, measure the coordinates, and then place it back on top of the leveling feet. The coordinates of the point depend on the origin of the cartesian coordinate system chosen by the students. The origin can be any point on top of the clear acrylic. A schematic diagram of the setup is shown below.

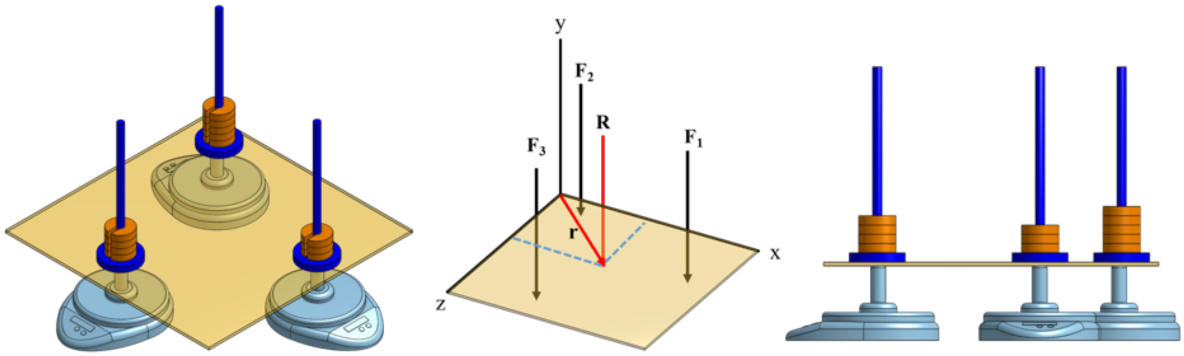

Figure 7: A schematic diagram of the experimental setup

Here, three loads represent a parallel system of forces $F_1, F_2,\ and\ F_3$. This parallel system of forces is then reduced to a force-couple system as follows to find out the magnitude of the resultant force and its point of application on the acrylic.

$$R = \sum F = F_1 + F_2 + F_3 \tag{1}$$

$$\sum M_O^F = M_O^{F_1} + M_O^{F_2} + M_O^{F_3} \tag{2}$$

$$M_O^R = r \times R = \sum M_O^F \tag{3}$$

Where, R is the resultant force, r is the position vector of the resultant force one xz plane (figure 7), $\sum M_O^F$ is the sum of moments at origin for all parallel forces, and M_O^R is the moment at origin for the resultant force. After determining the position vector of, r, from equation (2), a marker is used to mark the point on top of the acrylic (Fig. 8a) with respect to the origin that was chosen initially.

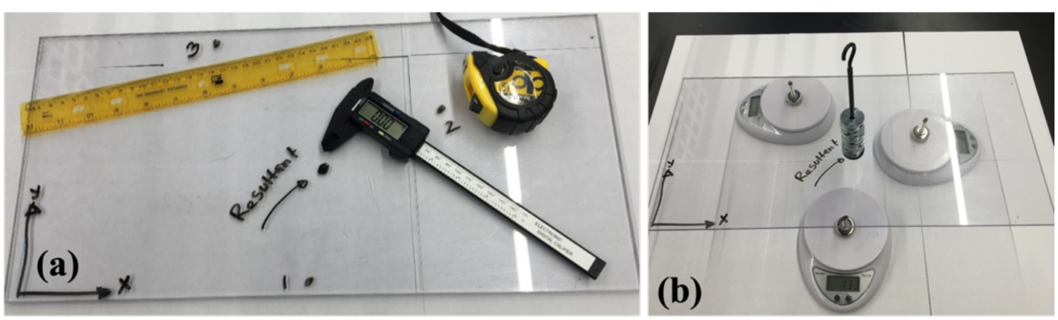

Figure 8: Position vector of the resultant force

All the masses from three hangers are combined into one single hanger. It is to be remembered that the weight hangers also have their own mass that needs to be count as well while combining all masses into one single weight hanger. To verify the position vector, r, the weight hanger with combined masses is placed on top of the resultant point marked on top of the acrylic (Fig. 8b). At this stage, the readings on the measuring scales are noted. The corresponding reaction forces on the digital scales should be the same as the loads of $F_1, F_2,\ and\ F_3$. A percentage difference within the range of $0 - 5\%$ is accounted for considerable measurements and calculations of the experiment.

Possible addition to the Demonstration Unit:
A similar experiment can also be conducted (not performed in the classroom yet) by using a homogeneous acrylic with composite areas. A schematic diagram is shown below. In this demonstration, the weight of the acrylic acting through its center of gravity will be another point of load along with the three weight hangers.

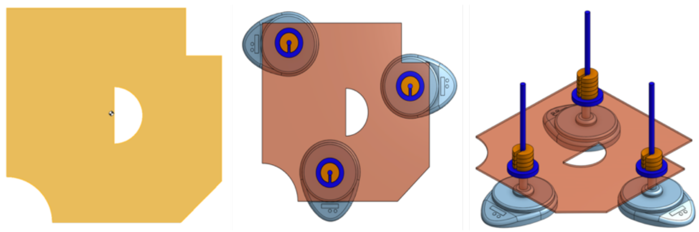

Figure 9: Schematic diagram of a system of parallel forces with a block of composite area

Before performing this experiment with a composite area, students also require a basic understanding of Distributed forces: Centroids and the Center of Gravity. A small-scale version of a composite area (Fig. 10) with homogeneous material was prepared and used in the classroom to find the center of gravity only [7]. A bigger version of this composite area with acrylic is required to perform the demonstration of simplifying a system of parallel forces.

Figure 10: Demonstration of the center of gravity of composite areas and volumes

Conclusion:
In the demonstration unit, there is no predefined origin or coordinate system such as those found in textbook exercise problems. This encourages students to inquire about how to define coordinates and determine an appropriate origin. As a facilitator, I guide them toward understanding the concept of a rectangular coordinate system. Students are encouraged to freely choose their coordinate system and designate any point on the unit as the origin. This approach fosters a deeper understanding of coordinate systems and encourages critical thinking in problem-solving. This demonstration unit was used in the classroom for several academic years. There is no formal assessment has been taken after using this unit other than a reflection in laboratory reports. The author will conduct a formal and summative assessment of this demonstration unit along with other demonstration units that are currently used in the classroom.

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