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# Providing Hands-On Context to Frames and Machines Analysis

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## Introduction

Analysis of Frames and Machines describes how two classifications of multi-member objects ("frames" and "machines") can be analyzed using groups of related equilibrium equations. In the case of machines, multi-member objects presented to students for analysis include a significant number of objects that students are unlikely to be familiar with. This is of concern since students' ability to predict the relative motions between interacting members supports an understanding of anticipated force transmission between members and provides a context through which to interpret results. Students could familiarize themselves with multi-member objects via lab exercises that require interaction with such objects; however, a search for such labs suggests that this has received limited attention. Therefore, a potential area for growth is the development of lab exercises related to frames and/or machines in order to provide opportunity for students to interact with multi-member objects thus developing their intuition with respect to such objects. A reasonable starting point would be to develop a lab focused around a classification of machines that are currently addressed with high frequency by existing textbooks; the focus of this paper is the description of such a lab exercise as well as the response of an initial cohort of students.

*Context*

The lab exercise described here was developed for a four-credit sophomore level engineering mechanics course that incorporates topics in statics and dynamics; the course includes a laboratory component. The course is part of the required curriculum in the Engineering program at James Madison University; the program is not discipline specific.

*Classification of frames and machines*

Analysis of frames and machines is a topic that typically follows coursework in equilibrium of forces and moments; it describes how multi-member objects can be analyzed using a group of related equilibrium equations. For this article, eight textbooks were reviewed to provide basis for observations related to typical presentation of the frames and machines topic. The eight textbooks are:

- Statics: Analysis and Design of Systems in Equilibrium; Sheppard and Tongue [1]
- Vector Mechanics for Engineers, Statics and Mechanics; Beer, Johnston, Mazurek, Cornwell, and Self [2]
- Engineering Mechanics: Statics; Meriam and Kraige [3]
- Engineering Mechanics: Statics and Dynamics; Costanzo, Plesha, and Gray [4]
- Engineering Statics; Condoor [5]
- Engineering Mechanics: Statics and Dynamics; Hibbeler [6]
- Engineering Mechanics: Statics and Dynamics; Bedford and Fowler [7]
- Engineering Mechanics: Statics; Riley and Sturges [8]

Although textbooks vary somewhat in their descriptions, a multi-member object containing at least one multi-force member would be appropriate for analysis by the methods presented in a frames and machines section of a textbook. Distinction between “frames” and “machines” is typically made along the following lines: frames are designed to support loads; machines are designed to transmit loads. Textbook sections that address frames and machines do not introduce any physical principles; rather, the focus is to harness previously introduced principles and methods to solve more complex systems.

*Potential issues with typical problem contexts*

Consistent with the observation that the focus of frames and machines sections of textbooks is to harness previously introduced physical principles and solution methods is the apparently typical approach of presenting problem solving strategies that are followed by a series of example problems. In the case of machines, the objects presented to students for analysis include a significant number of objects that students are not familiar with. For instance, the textbook used by the author relies significantly on examples based on heavy equipment and hand tools while students in the author’s program have limited experience with either. When informally questioned about how the extension of a hydraulic cylinder would affect the orientation of an excavator bucket students demonstrated a lack of ability to anticipate how the bucket would move (i.e. what point the bucket would pivot around), and how a hydraulic cylinder worked (i.e, that it extends and retracts). Likewise, with hand tools based on designs more complex than simple levers, students were unlikely to “see” how a locking pliers worked or how a bolt cutter makes use of a compound lever to develop a large mechanical advantage. This is of concern since students’ ability to predict the relative motions between interacting members supports an understanding of anticipated force transmission between members and provides a context through which to interpret results. In order to provide an academic framework for these informal observations consider the review of how experts think about learning provided by Venters and McNair [9] which indicates that recent views of learning stress the value of genuine context (situative) rather than purely processing information within the mind (cognitive). If the problems presented to students to both learn from and to practice on are based on objects that are outside of the typical student experience, the learning mode is solely cognitive.

Another academic perspective that is particularly germane to analysis of machines is provided by the observations of Steif [10] who makes the claim that the skills required in Statics include mathematical skills as well as “less recognized skills” including the ability to:

- Discern separate parts of an assembly and where each connects to others
- Discern surfaces of contact between connected parts and/or the relative motions that are permitted between two connected parts

Comparison of the skills suggested by Steif and the author’s observations of student capabilities to anticipate motions within linkages indicates a gap, further validating the authors concerns.

Providing an activity that offers students opportunity to gain experience with machines similar to objects typically presented in textbooks would provide genuine context while promoting students abilities to discern separate parts and predict relative motions. As such it would expand learning into the situative mode as well as directly addressing the requirements of Steif.

Hadim et al [11] as well as Boylan-Ashraf et al [12] provide examples of linking Statics topics to hands-on activities. Hadim describes linking a traditionally taught mechanics course (inclusive of statics topics) to a design laboratory course that includes demonstrations and hands-on activities. Hadim indicates advantages that extend into the domain of "soft skills" (a.k.a. "essential skills") as advocated by ABET 2000. A more recent example is provided by Boylan-Ashraf who includes hands-on lab activities as part of an arsenal of active strategies applied in an introductory solid mechanics course (based on presented topical coverage the course would serve as a course in statics). Indicated advantages of active strategies include their increased likelihood (compared to lecture-based activities) to provide experiences that are significant enough to build connections as well as a strong association with improved self-efficacy. It is further suggested that hands-on learning may promote student retention.

*Developing contextual knowledge for the "machines" topic*

In spite of the potential advantages of providing relevant contexts for frames and machines problems, a search for such labs suggests that this has received limited attention. As an indicator of absence, consider the comparison of two searches of the ASEE website [13], one including [statics AND lab AND truss], and the other including [statics AND lab AND “frames and machines”]. The first search (truss) yielded 382 results while the second (frames and machines) yielded nine. Of the nine results, only two included some level of detail on actual lab activities related to frames or machines, and only one activity was directed at machines. Furthermore, the sole activity directed at machines may be better classified as a "moment balance" problem than a "machines" problem since analysis of multi-force members is not required.

Therefore, a potential area for growth is the development of lab exercises related to frames and/or machines in order to provide opportunity for students to interact with multi-member objects as a way to develop their intuition with respect to such objects. A reasonable starting point would be to develop a lab focused around a classification of machines that are currently addressed with high frequency by existing textbooks. The seven textbooks indicated above were reviewed to observe and categorize the machine artifacts presented for analysis in order to determine if a typical set of contexts could be identified. The review addressed only problems for which a picture or diagram was presented; diagrams that were not perceived as an attempt to represent a real artifact were not included in the review. The results of the review are presented in table 1, below.

| | Sheppard and Tongue [1] | Beer, Johnston, Mazurek, Cornwell, and Self [2] | Meriam and Kraige [3] | Costanzo, Plesha, and Gray [4] | Condoor [5] | Hibbeler [6] | Bedford and Fowler [7] | Riley and Sturges [8] | TOTAL |
|---|---|---|---|---|---|---|---|---|---|
| **pliers/cutters** | 11 | 5 | 4 | | | 5 | 7 | 4 | 36 |
| **clamping mechanism (non-pliers/cutters)** | 1 | 5 | 14 | 1 | | 4 | | 4 | 29 |
| **hydraulic construction equipment** | | 6 | 6 | 4 | | 2 | 6 | 2 | 26 |
| **load lifter** | | 6 | 6 | 2 | | 5 | | 4 | 23 |
| **mechanism (other)** | 1 | 4 | 3 | 3 | | | 1 | 3 | 15 |
| **vehicle** | | | 2 | 1 | | 3 | 2 | | 8 |
| **kinesiology** | 1 | | | | | 2 | 2 | | 5 |
| **pump** | 1 | | 1 | 1 | | 1 | | | 4 |

**Table 1: Tally of machine contexts presented by textbook**

The review indicates that although some variation exists between textbooks, it can generally be said that clamping mechanisms (pliers/cutters and non-pliers or cutter) are the most referenced objects, followed by construction equipment (note that one textbook included no machines problems). Parsing pliers/cutters versus non-pliers/cutters examples becomes less amenable to generalizations, however four of the six textbooks that include machine problems include at least as many pliers/cutters problems as non-pliers/cutters clamping mechanism problems. The review supports the assertion that a laboratory activity focused on hand operated pliers or cutters would provide appropriate contextual support for a significant fraction of textbook problems.

## Description of laboratory activity

The laboratory activity is implemented in a sophomore level mechanics course that incorporates topics in statics and dynamics; the course also includes a laboratory component. In order to fit the activity into the existing schedule a truss-based activity was removed. The laboratory activity is cast as a reverse engineering exercise in which the students are placed in the role of an engineer at a hand tool company; their task in this role is to benchmark tools manufactured by a competitor. Students are presented with three hand tools: one bolt cutter and two pliers. The bolt cutter represents a class of hand tools based on a compound lever while the pliers represent simple levers. In addition to providing a force amplification analysis of the bolt cutter, students respond to an open-ended prompt to compare the tools presented to them.

Students perform a cutting activity in which they are directed to cut a variety of rods with the hand tools; the rods vary in material properties as well as physical size. The combination of the cutting activity and the comparison prompt is intended to make the students mindful of the workings of the tools they are using and to go beyond the level of interaction that might occur in a typical training session that would cover appropriate (safe) usage of the same tools.

*Materials and tools used in laboratory activity*

Although students are only required to determine the force amplification associated with one bolt cutter during the initial cutting of one size (diameter) of material, it was decided that providing a range of bolt cutters and material sizes was appropriate. Bolt cutter force amplification changes continuously as the handles are brought together to create the pinching motion. Therefore the force amplification at the initial cutting of the material is different for different sizes of material. A combination of three bolt cutters and three material sizes supports variation in required student work. The variation is intended to allow students to collaborate on solution techniques while generally reducing opportunity for direct sharing of solutions.

Materials and tools similar to those obtained for the activity are readily available from major home improvement retailers and industrial suppliers. Four different rods were provided for cutting; one six foot length of all four rods can be purchased for less than $25. The selection of rods was comprised of three different sizes and two different materials as shown in table 2, both copper and steel were included to provide additional experiential range to the cutting activity.

**Table 2: Materials Provided for the Cutting Activity**

| Diameter (inch) | Material |
|---|---|
| 1/16 | O-2 Precision Ground Tool Steel |
| 1/8 | O-2 Precision Ground Tool Steel |
| 3/16 | O-2 Precision Ground Tool Steel |
| 1/8 | Multipurpose 110 Copper |

Three different sizes of bolt cutters and two linesman's pliers we obtained for the activity; the group of five tools costs less than $90. Descriptions of the tools are provided in table 3.

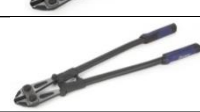
| Description | Image |
|---|---|
| 7 inch lineman's pliers |  |
| 9 inch lineman's pliers |  |
| 8 inch bolt cutter |  |
| 14 inch bolt cutter |  |
| 24 inch bolt cutter |  |

**Table 3: Descriptions and Images of Tools Used in Activity**

Both of the lineman's pliers and the 8 inch bolt cutter are designed to be operated by a single hand while the remaining bolt cutters require two hands to operate.

*Student work*

During the course of the lab students perform tool operation (cutting activity) as well as modeling (force amplification calculation). For the cutting activity students are instructed to make multiple cuts of the materials with each tool and then to write a brief review that compares operation of each tool in a format appropriate for a contribution to an online review of the tools. To determine force amplification for their specific combination of bolt cutter and material, students are directed to insert the rod to be cut as deeply into the cutting jaws as it will go. Students are directed to assume that operator force is applied at the center of the logo on each grip. These constraints establish a reasonably repeatable and predictable spatial configuration of the bolt cutter and location of applied force thereby simplifying evaluation of student-calculated values of force amplification.

Solutions provided by students are required to include:

1) a dimensioned drawing of the assembled tool with the handle at the angle that accommodates their material
2) free body diagrams necessary to allow calculation of forces at each pin
3) equilibrium equations in support of free body diagrams as appropriate
4) free body diagrams of each component that indicate the forces that were determined to be applied to each pin as a function of operator input force
5) The input:output force relationship between operator force input and force applied to the material at the start of the cut (while material cross-section is still full size)

In order to complete the first solution requirement students must position their bolt cutter handles to properly accommodate their assigned material size and then make a number of measurements that will inform their free body diagram. Students have access to dial calipers, tape measures, and protractors to make measurements. The second and third solution requirement are the essence of a textbook "machines" problem, it is anticipated that they will lead to determination of the forces applied to each pin (for use in requirement four) as well as the force amplification value (for use in requirement five). The fourth solution requirement specifies the report-out format to be a free body diagram inclusive of force values while requirement five is simply a statement of the calculated force amplification.

*Opportunities for adaptation*

The activity described can be deployed as-is or could be adapted to better suit local students. Opportunities exist to simplify and streamline the problem, for instance one could suggest a small angle assumption for the jaw half angle, or remove the requirement to compare the bolt cutter to other tools. On the other hand the activity could be reworked to require more effort, for instance one could also require a force amplification analysis of the less complex lineman's pliers for comparison to the bolt cutter. Complexity could be increased by requiring students to develop a continuous solution of force amplification for the complete range of possible handle angles.

**Solution of force amplification problem**

The solution described below is intended to represent student work that fulfills the expectations of the first three requirements of the assignment and can be considered a proxy student solution. The presentation herein was developed by the author and is presented for the reader’s convenience; it is acknowledged that similar solutions certainly pre-exist. The proxy student solution is followed by a description of a method that can be used to determine solution parameters for a broad range of bolt cutters.

*Proxy student solution*

Figure 1 shows an image of a bolt cutter in the closed configuration with labels to establish a naming convention for the pin joints as well as the operator input locations.

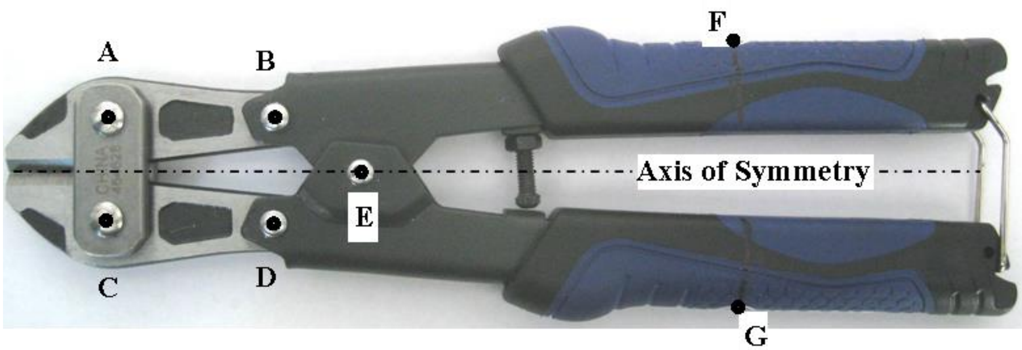



**Figure 1: Image of 8" bolt cutter with labels for pins and operator input locations**

The bolt cutter has five members total, due to symmetry not all five members of the bolt cutter require analysis; a typical solution would consider three members. Figure 2 demonstrates the connections of three members of a generic bolt cutter and includes the external forces due to the operator (F) and the reaction force at the rod being cut (H). Furthermore, figure 2 establishes a coordinate system that will be common to the free body diagrams of each individual member analyzed.

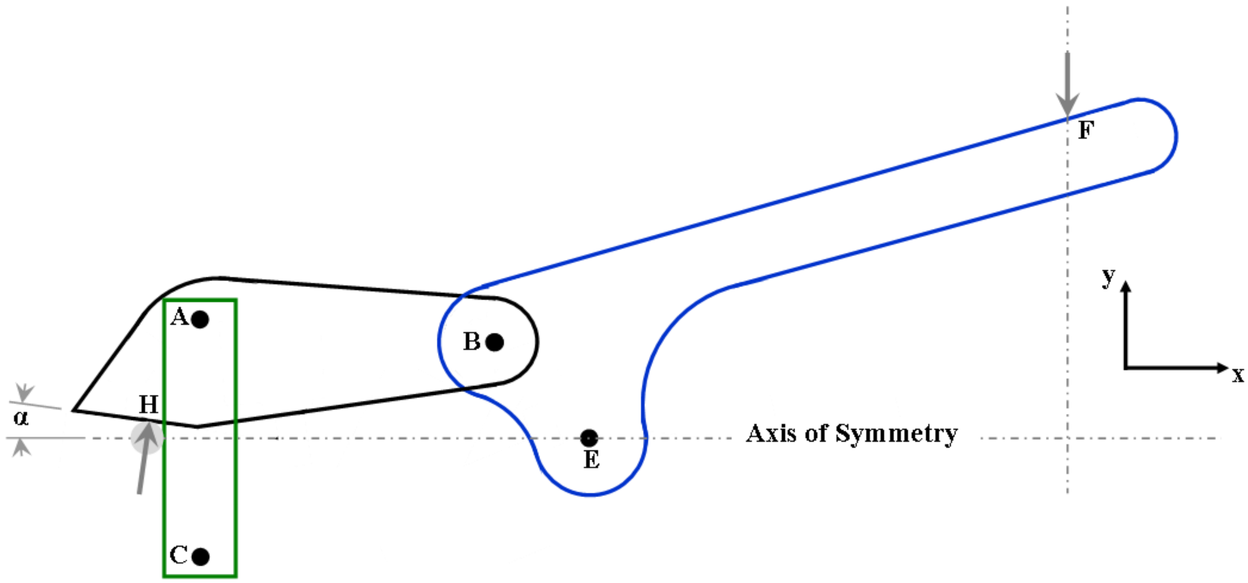



**Figure 2: Bolt cutter members and external forces**

Part one of an appropriate student solution would include similar information as shown in figure 2 as well as dimensions to locate the pins and external forces. Students are required to provide free body diagrams and equilibrium equations to represent their bolt cutter in support of their force amplification solution. Free body diagrams of the members AC, HAB, and BEF and their supporting equations follow.

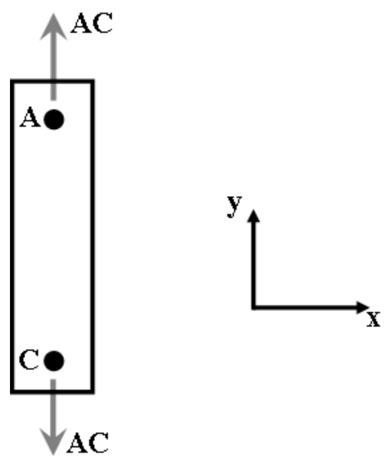



**Figure 3: Free body diagram of member AC**

The free body diagram of member AC shown in figure 3 demonstrates that AC is modeled as a two-force member and establishes an assumed direction of force AC at pin A. No equilibrium equations are necessary.

The free body diagram of member HAB shown in figure 4 demonstrates that it is a multi-force member; it includes the reaction force due to the rod being cut (H) as well as pin reactions at A and B.

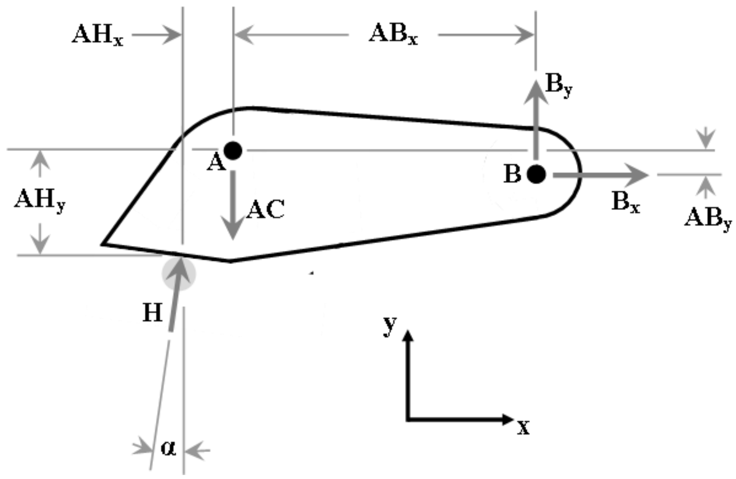



**Figure 4: Free body diagram of member HAB**

The diagram also establishes an assumed direction of the pin reaction forces $B_x$ and $B_y$. A set of equilibrium equations that support the free body diagram in figure 4 are provided as equations 1, 2, and 3 below:

$$\Sigma F_x = Hsin\alpha + B_x = 0 \tag{1}$$

$$\Sigma F_y = Hcos\alpha - AC + B_y = 0 \tag{2}$$

$$\Sigma M_A = (AB_x)B_y + (AB_y)B_x - (AH_x)Hcos\alpha + (AH_y)Hsin\alpha = 0 \tag{3}$$

It is not unusual for a bolt cutter to be used to cut relatively small rod sizes so that the jaws need not be opened significantly. This leads to a condition for which the jaw half angle (α) is small and could be treated as zero degrees to provide a reasonable approximation. In such a case, equation 3 should be replaced with equation 3a.

$$\Sigma M_A = (AB_x)B_y + (AB_y)B_x - (AH_x)H = 0 \tag{3a}$$

The free body diagram of link BEF shown in figure 5 demonstrates that it is a multi-force member; it includes the force applied by the operator (F) as well as pin reactions at B and E.

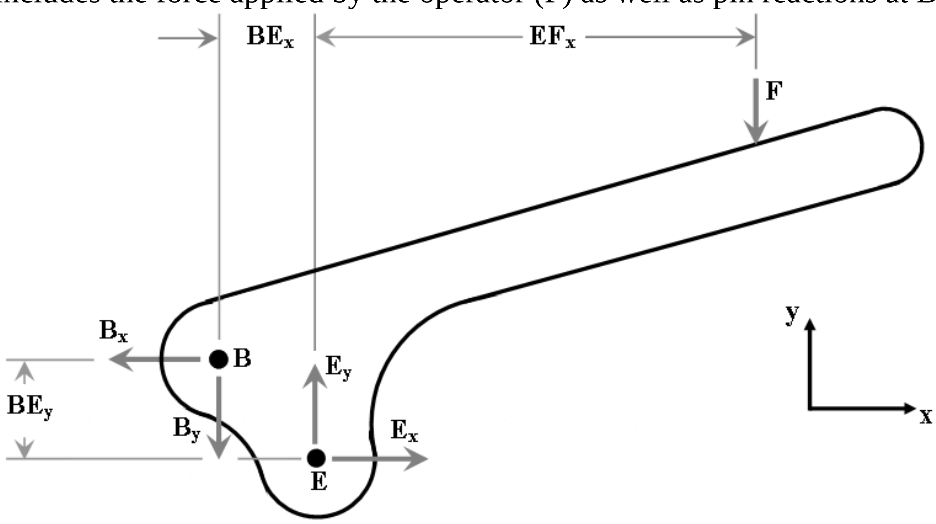



**Figure 5: Free body diagram of member BEF**

The reactions at pin B link the diagram and equations for BEF to the diagram and equations for HAB. A set of equilibrium equations that support the free body diagram of HAB in figure 5 are provided as equations 4, 5, and 6 below:

$$\Sigma F_x = -B_x + E_x = 0 \tag{4}$$

$$\Sigma F_y = -B_y + E_y - F = 0 \tag{5}$$

$$\Sigma M_E = (BE_x)B_y + \left(BE_y\right)B_x - (EF_x)F = 0 \tag{6}$$

Equations 1-6 include placeholders for distance dimensions ($AB_x$, $AB_y$, $AH_x$, $AH_y$, $BE_x$, $BE_y$, and $EF_x$) which are presumed to be known values measured by the students based on the assigned combination of bolt cutter and rod size. Equations 1-6 also include seven unknowns (AC, F, $B_x$, $B_y$, $E_x$, $E_y$, and F) and cannot be solved explicitly. However, the force amplification ratio (ratio of input force F to force on rod H) can be determined by considering the scenario in which the input force F is equal to 1. Assuming a value for F results in a system of six equations and six unknowns which can be solved for the pin reaction forces as well as the rod reaction force. The rod reaction force determined in this way is also the force amplification ratio since the input force is set to 1.

*Generalization of distance measurements*

The proxy student solution provided above is based on distance measurements determined by the student that are based on their assigned combination of bolt cutter and rod size. This section demonstrates a way to drive the required orthogonal distance measurements (e.g. $AB_x$ and $AB_y$) based on point-to-point measurements (e.g. length AB). This approach is motivated by potential reduction in effort to generate solutions and is intended to support extension of the assignment to a broad range of tools and rod sizes.

The author initially intended to drive the orthogonal distance measurements based on the size of the rod to be cut. Two issues with this approach made it unattractive. First, some pin-to-pin dimensions are sensitive to variation in the relatively small "jaw half angle" (α), second, it was observed that the jaws of some of the bolt cutters purchased exhibited a gap between the jaws in the fully closed condition that would significantly affect the jaw angle at rod contact. The approach shown here is based on the "handle half angle" (γ) where γ is defined as the angle between line EF and the axis of symmetry as shown in figure 6.

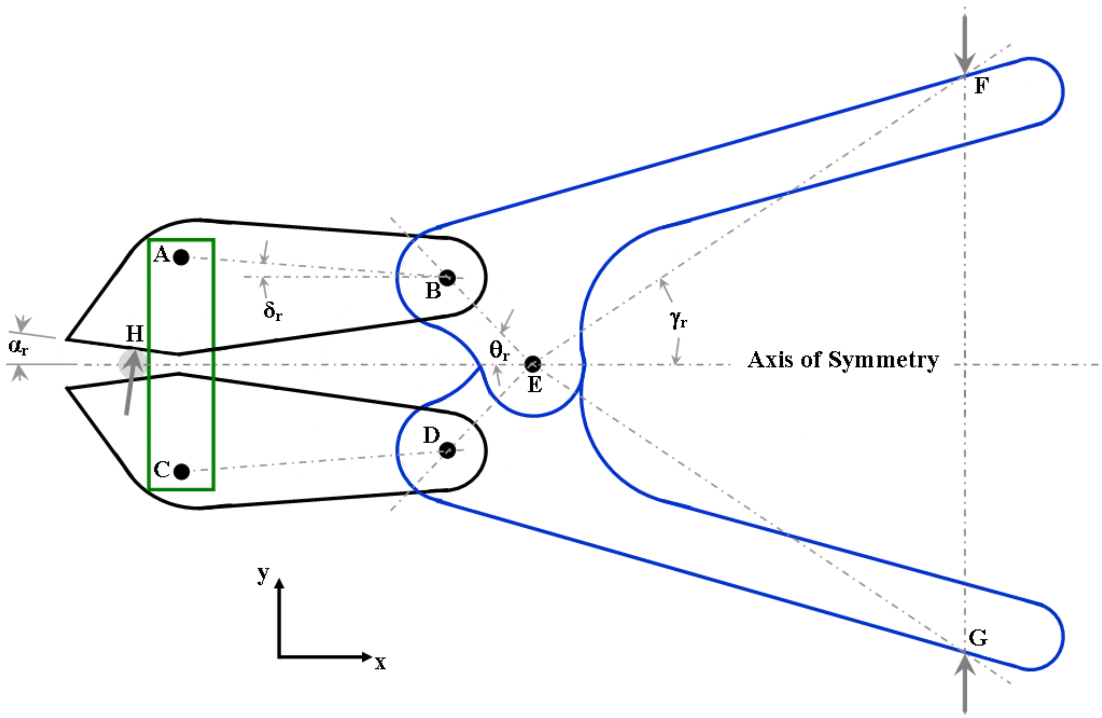



**Figure 6: Bolt cutter diagram with labels for pin joints, force input locations, and angles**

Dimensions that must be determined include constant values such as the distance between pin joints that are on the same member, and non-constant values such as the relative angles between pin joints that vary with handle position. Constant values include distances AC, AB, BE, and BF. The varying relative angles between members ($\gamma$, $\theta$, and $\delta$) can be determined from pin to pin distances between pins on different members while the tool is in a configuration of interest. It is convenient to determine the varying angles $\gamma$, $\theta$, and $\delta$ in the closed position ($\gamma_c$, $\theta_c$, and $\delta_c$) as well as for the configuration in which the jaws contact a rod of radius r ($\gamma_r$, $\theta_r$, and $\delta_r$). The author chose to rely on distance measurements to determine angular measurements since use of a protractor to measure angles on the tool proved cumbersome.

Figure 7 is a stick diagram that represents member BEF in the closed configuration as well as in a configuration that corresponds to jaw contact with a rod of radius *r*.

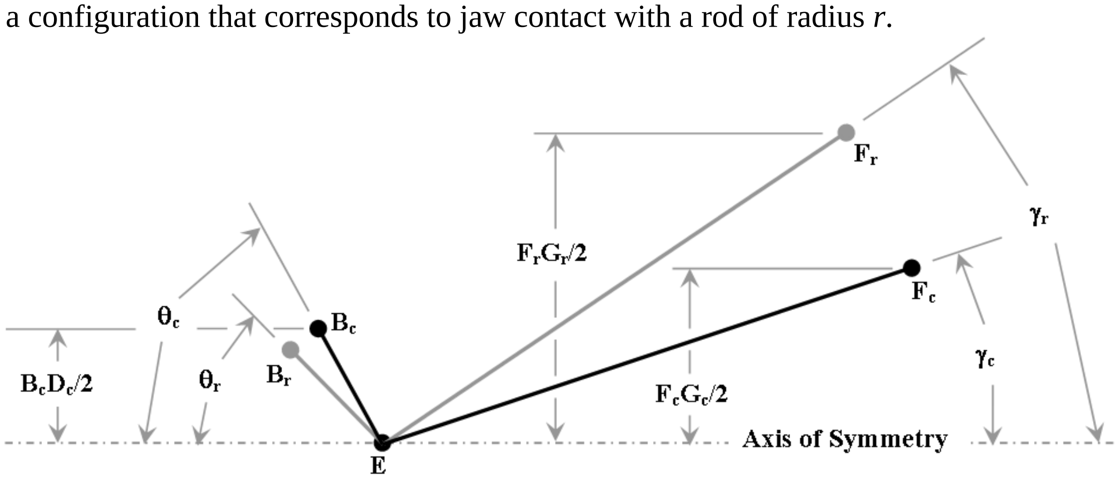



**Figure 7: Stick diagram of member BEF in closed and partially open configurations**

In figure 7 points $B_c$ and $B_r$ represent the location of point B in the closed configuration and in the configuration in which the jaws contact a rod of radius r respectively. Points $F_c$ and $F_r$ similarly represent the location of point F in those configurations. The distance measurement approach leads to the following equations for angles $\gamma_c$, $\theta_c$, $\gamma_r$, and $\theta_r$:

$$\gamma_c = sin^{-1}\left[\frac{F_cG_c/2}{EF}\right] \tag{7}$$

$$\theta_c = sin^{-1}\left[\frac{B_cD_c/2}{BE}\right] \tag{8}$$

$$\gamma_r = sin^{-1}\left[\frac{F_dG_d/2}{EF}\right] \tag{9}$$

$$\theta_r = \theta_c - (\gamma_d - \gamma_c) \tag{10}$$

Where:

$\gamma_c$ = angle described by a line from pin joint E to the force input location F (for the "closed" configuration) and the axis of symmetry (calculated)

$\theta_c$ = angle described by a line from pin joint E to pin joint B (for the "closed" configuration) and the axis of symmetry (calculated)

$\gamma_r$ = angle described by a line from pin joint E to the force input location F (for the configuration in which the jaws contact a rod of radius *r*) and the axis of symmetry (calculated)

$\theta_r$ = angle described by a line from pin joint E to pin joint B (for the configuration in which the jaws contact a rod of radius *r*) and the axis of symmetry (calculated)

$F_cG_c$ = distance between force input points F and G in the "closed" configuration (measured)

$B_cD_c$ = distance between pin joints F and G in the "closed" configuration (measured)

$F_rG_r$ = distance between force input points F and G for the configuration in which the jaws contact a rod of radius *r* (measured)

*EF* = fixed distance between pin joints E and F (measured)

*BE* = fixed distance between pin joints B and E (measured)

With the angles described in figure 7 established, the distances between pin joints along the x and y axes can be determined as shown:

$$EF_x = EFcos\gamma_r \tag{11}$$

$$BE_x = BEcos\theta_r \tag{12}$$

$$BE_y = BEsin\theta_r \tag{13}$$

Where $EF_x$, $BE_x$, and $BE_y$ represent distances between pin joints along x and y axes for the configuration in which the jaws contact a rod of radius *r*.

A similar approach is applied to a partial stick diagram of member HAB shown in figure 8:

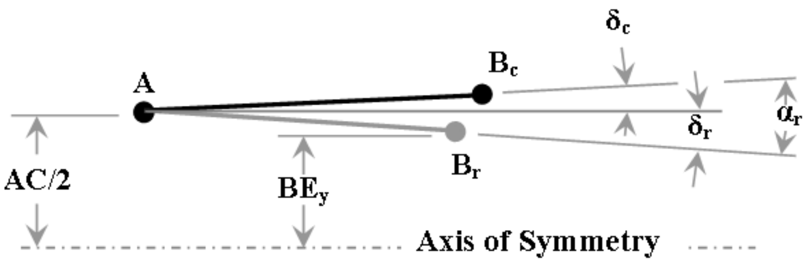



**Figure 8: Partial stick diagram of member HAB in closed and partially open configurations**

The angles $\delta_c$, $\gamma_d$, and $\alpha_r$ can be determined from measured pin to pin distances and distances determined from the previous diagram.

$$\delta_c = sin^{-1}\left[\frac{\frac{B_C D_C}{2} - \frac{AC}{2}}{AB}\right] \tag{14}$$

$$\delta_r = sin^{-1}\left[\frac{\frac{AC}{2} - BE_y}{AB}\right] \tag{15}$$

$$\alpha_r = \delta_c + \delta_r \tag{16}$$

Where:

$\delta_c$ = angle described by a line from pin joint A to pin joint B (for the "closed" configuration) and a reference line parallel to the axis of symmetry (calculated)

$\delta_r$ = angle described by a line from pin joint A to pin joint B (for the configuration in which the jaws contact a rod of radius *r*) and a reference line parallel to the axis of symmetry (calculated)

$\alpha_r$= angular change of member HAB (relative to "closed" configuration) due to positioning jaws to contact a rod of radius *r*; also the "jaw half angle" (calculated)

$B_cD_c$ = distance between pin joints F and G in the "closed" configuration (measured)

*AC* = fixed distance between pin joints A and C (measured)

*AB* = fixed distance between pin joints A and B (measured)

$BE_y$ = y axis distance between pin joints B and E (for the configuration in which the jaws contact a rod of radius *r*) determined from equation (13)

With the angles described in figure 8 established, the distances between pin joints along the x and y axes can be determined:

$$AB_y = \frac{AC}{2} - BE_y \tag{17}$$

$$AB_x = ABcos\delta_r \tag{18}$$

Where $AB_x$, and $AB_y$ represent distances between pin joints along x and y axes for the configuration in which the jaws contact a rod of radius *r*.

Figure 9(a) and 9(b) depict half of member AC and a close up view of the jaw/rod interface respectively.

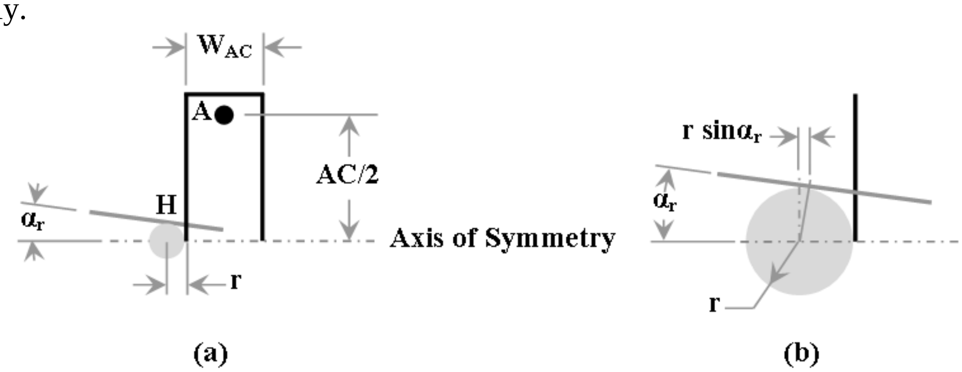



**Figure 9: Partial diagram of member AC including rod**

The angle $\alpha_r$ is the jaw half angle associated with contact with a rod of radius *r* as calculated in equation (16). Based on that calculation the distances from pin A to the location of the reaction force due to the rod can be determined along the x and y axes as follows:

$$AH_x = \frac{W_{AC}}{2} + r - r sin\alpha_r \qquad (19)$$

$$AH_y = \frac{AC}{2} - r cos\alpha_r \qquad (20)$$

Where:

$\alpha_r$ = jaw half angle as calculated in equation (16)
$W_{AC}$ = width of member AC (measured)
$AC$ = fixed distance between pin joints A and C (measured)
$r$ = radius of rod to be cut measured)

Distances $AH_x$, and $AH_y$ represent distances between pin joint A and rod reaction at point H along x and y axes for the configuration in which the jaws contact a rod of radius $r$. It is assumed that the rod will be seated in the jaws so that it contacts member AC.

Equations 11, 12,1 13, 17, 18, 19, and 20 provide the pin to pin distances along the x and y axes required in equations 1-6 and support solution of equations 1-6 for a broad range of bolt cutters and rod sizes.

**Student response to laboratory activity**

A small cohort of students were assigned the laboratory activity in order to get initial feedback. These students were prompted for their opinion of the bolt cutter laboratory activity as part of the course assessment at the end of the semester. Student opinions were assessed using one Likert scale response and one free response. The students were asked to rate their level of agreement with the statement **I am confident in my ability to apply Frames and Machines analysis to a real frame or machine** on a five point scale (1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, 5: strongly agree). More than 80% of the cohort indicated some level of agreement with the statement. Students were also presented with an open ended prompt to provide feedback on the bolt cutter laboratory activity. Responses are provided below:

1. This was cool because I was able to apply what I have learned to something in real life. Also it taught me (that) in order to solve a problem effectively you have to be good with your hands as well as your mind to be able to accurately analyze a problem
2. Helped to understand/ingrain concepts better
3. was not too difficult a problem
4. instructions were a little unclear
5. very easy to understand

Only (1) overtly addresses the physical nature of the problem, although (2) also suggests that something extra was gained from the activity. Response (3) typifies a fairly unreflective reaction possibly based on a surface or strategic learning approach to learning (I was able to complete the problem successfully so it was ok). Responses (4) and (5) also seem to come from a surface or strategic learning perspective and illustrate the ambiguity that can be associated with survey responses.

## Conclusion

A laboratory activity related to analysis of machines was developed in which students must operate a bolt cutter and make measurements to support a force analysis. Because the activity requires interaction with a real object in the process of developing a frames and machines solution to a force amplification problem, it is assumed that it provides a more significant experience than simply processing a book problem. It has also been stated that the ability to predict how various parts of a device work together is a skill that stands alongside mathematical ability as a required skill in statics. As a representative of the general class of "pliers" problems the bolt cutter activity provides hands-on exposure to a type of problem frequently encountered in textbooks, thereby providing opportunity for students to derive enhanced understanding that is directly related to typical homework problems.

Transferability opportunities are enhanced by the level of detail provided on the activity, the proxy solution provided, and the generalization of variable dimensions used in the proxy solution. Furthermore, suggestions that would either reduce or increase the anticipated level of student effort required to complete the assignment are provided.

Student response to the activity can generally be categorized as positive: more than 80% of students indicated confidence in their ability to apply a frames and machines analysis to a real object. Based on free responses it can be said that some students appreciated the link between theory and practice.

The activity has gained interest at the author's institution where two additional instructors have adopted it. It is anticipated that it will evolve as a result of broader deployment.

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## References

[1] S. D. Sheppard and B. H. Tongue, Statics Analysis and Design of Systems in Equilibrium (revisd edition), Danvers, MA: John Wiley & Sons, Inc., 2007.

[2] F. P. Beer, E. R. Johnston, Jr., D. F. Mazurek, P. J. Cornwell and B. P. Self, Vector Mechanics for Engineers (11th edition), New York, NY: McGraw-Hill, 2016.

[3] J. L. Meriam and L. G. Kraige, Engineering Mechanics Statics (sixth edition), Danvers, MA: John Wiley & Sons, 2010.

[4] F. Costanzo, M. E. Plesha and G. L. Gray, Engineering Mechanics Statics and Dynamics (second edition), New York, NY: McGraw-Hill, 2013.

[5] S. S. Condoor, Engineering Statics (third edition), Schroff Development Corproation, 2009.

[6] R. C. Hibbeler, Engineering Mechanics Statics and Dynamics (13th edition), Upper Saddle River,

NJ: Pearson Prentice Hall, 2013.

[7] A. Bedford and W. Fowler, Engineering Mechanics Statics and Dynamics (fifth edition), Upper Saddle River, NJ: Pearson Prentice Hall, 2008.

[8] W. F. Riley and L. D. Sturges, Engineering Mechanics: Statics, John Wiley & Sons, 1996.

[9] C. Venters and L. McNair, "Learning Statics: A Cognitive Approach," in *ASEE Southeast Section Conference*, 2010.

[10] P. S. Steif, "An Articulation of the Concepts and Skills Which Underlie Engineering Statics," in *34th ASEE/IEEE Frontiers in Education Conference*, Savannah, GA, 2004.

[11] H. Hadim, D. Donskoy, K. Sheppard, B. Gallois and J. Nazalewicz, "Teaching Mechanics to Freshmen by Linking the Lecture Course to a Design Course," in *ASEE 2000 Annual Conference*, St. Louis, MO, 2000.

[12] P. C. Boylan-Ashraf, S. L. Billington and S. Sheppard, "Using Online and hands-on activities to improve self-efficacy in mechanics," in *122nd ASEE Annual Conference & Exposition*, Seattle, WA, 2015.

[13] "https://peer.asee.org," [Online]. [Accessed 14 December 2016].