Multimedia Simulation Tool for Steel Tension Member Analysis and Design

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Abstract

This paper presents a multimedia simulation tool that allows for the investigation of steel tensile member connection analysis and design. The motivation behind the creation of this software is to meet the needs of students and their different learning styles for the education of tensile member connections. A computer aided teaching tool called *Tension Connection Analyzer* was developed to serve both students and instructors as a supplemental device for the topic of steel tensile member analysis and design. The intent of the software is to enhance the student's ability to visualize the failure modes that exist in steel tension member connected systems. The overall objective of the software is to produce an aide to improve the classroom experience, while at the same time allow students to develop a feel for steel tension member design outside of the classroom.

1 Introduction

Simulation allows for real time evaluation to be performed in given systems through the use of computer-aided design. In the area of education, simulation has the ability to enhance topic comprehension without causing an increase in necessary lecture time. Yet, while the positive aspects of simulations and computer aided design (CAD) are recognized by educators, topic specific educational software packages remain small in number. Among the software developed for civil engineering education in recent years, the West Point Bridge Designer[1] developed by Dr. S. Resseler at the West Point is perhaps the most popular, most widely known engineering design software for education purpose. Although the software was developed intending for outreach to middle to high school students, it has attracted the attention of college students and faculty as well. The software also helps set the benchmark as what an educational software should be.

The motivation in developing the *Tension Connection Analyzer* was that of enhancing the student's ability to visualize the failure modes that exist in steel tension member connected systems. The specifications for tensile member connections, found in the American Institute of Steel Construction's (AISC) Load and Resistance Factored Design (LRFD) manual[2], require a knowledge of the grades of steel, member cross sections, bolts, etc. in order to investigate the functionality of a particular connection. Furthermore, each connection has a potential to fail in different form (called modes) and in different patterns (called paths). With all of these parameters and conditions in mind, it becomes apparent that actual hands-on examples can become very costly. Current in-class illustration includes small scale models of the before or after version of tensile member system. Each model only shows the failure mode due to a specific loading condition. While an example of this nature does allow students to see how a particular system reacts to a given load, it does not exemplify the dynamic propagation of the failure through the material and it does not allow for any variation of the parameters. For example, the students cannot physically view the various paths of crack propagation that exist in block shear studies.

The computer program *Tension Connection Analyzer* was designed to link together the abstract theory with the real-world visualization in the teaching of tensile member connection design. During the development of the program, it was recognized that students have different learning styles. Some are theoretically oriented while some prefer hand-on methods. Students with the theoretical learning styles are those who are satisfied with the theory behind a particular procedure and do not require a practical application in order to fully grasp the topic[3]. While on the opposite end of the spectrum, the students that are of a sensing nature want specific examples that give real-world applications. In order to accommodate the wide range of learning style and to fulfill the educational needs, the program is composed of 2 separate modes, an “analysis” mode and a “demo” mode.

In the “analysis” mode, the program

- allows the user to determine the load capacities of specific failure paths;
- permits the user to input all the variables necessary to define a particular fracture and block shear path; and
- shows the calculations performed in determining the design strength of the connection.

In the “demo” mode, the program

- gives the user the ability to select a failure demonstration from a choice of six different connection patterns;
- takes the user to a screen showing the governing equations along with a “VCR” that presents the user with a series of failure animations from which to choose; and
- shows the calculations of the dominating failure mode.

The paper focuses on the features of the software and the user’s guide in using the software. The failure modes of steel tension connection are briefly described. The presentation will be a demonstration of how the software works and the output of the analyses and demonstrations. The software is available in the authors’ web site (http://www.engr.utk.edu/~pionke).

2 Steel Tension Connection Failure Modes

2.1 Failure Modes

The testing of a tensile member and its connection determines the axial loading capacity that a member can resist without failure. Figure 1 exemplifies the application of axial load used in the testing of tensile members. This testing encompasses failure due to either the yielding of its gross cross-sectional area, the fracture (separation) of the member through the bolt holes, or a combination of fracture and yielding at the connected area. These three forms of failure are classified as: tensile yield, tensile fracture, and block shear rupture.

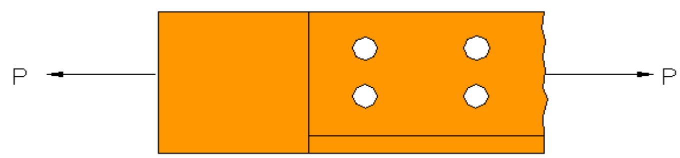

Figure 1 Tensile Load

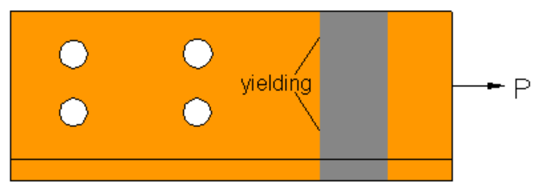

Figure 2 Example of Tensile Yield

Tensile yield occurs when the load placed on a cross-section reaches the yield strength of the material. Failure of this manner occurs away from the connection, as can be seen in Figure 2.

Tensile fracture is the separation of a member under an axial force. Tensile fracture occurs at the path that has the least resistance. Hence, a path through the bolt holes would be more likely to fail than one through a section away from the connection. Figure 3 shows one of the possible fracture paths under axial force P.

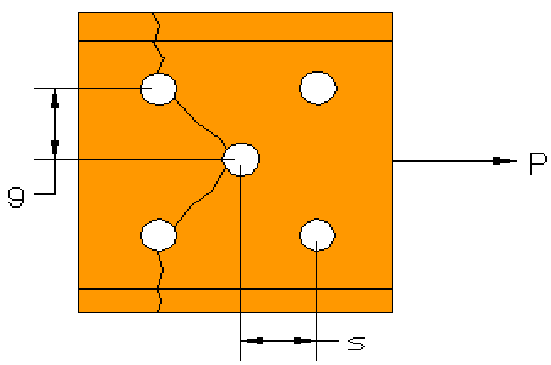

Figure 3 Example of Tensile Fracture Path

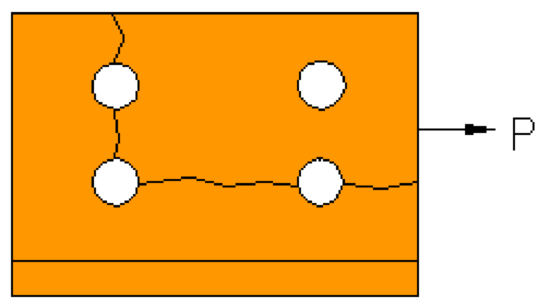

Figure 4 Example of Block Shear Path

Block shear is a combination of yielding and fracture. It is a limit state that is determined by the sum of the shear strength and tensile strength along a particular failure path. An example of block shear can be seen in Figure 4. For all designs, all three failure modes must be studied in order to determine the limiting design strength for a given tensile member.

2.2 Design Strength

For any design, the design strength of tension members, *T*, shall be the lowest value obtained according to the limit states of yielding in the gross cross-section, fracture in the effective net section, and the shear rupture (block shear). The following sections briefly describe the design criteria for each of the limit states. For detail discussion of tensile member design, the readers are encouraged to refer to any structural steel design textbooks. A comprehensive design example is also available in Williams[4].

2.2.1 Yielding

For yielding in the gross cross-section, the tensile yield design strength T_t is defined as [reference 2, Section D].

$$T_t = \phi_t P_{nt} = \phi_t A_g F_y \tag{1}$$

where $\phi_t = 0.9$, A_g = gross cross-sectional area of member, and F_y = yield stress. The gross area of a member at any point is the sum of the products of the thickness and the gross width of each element measured normal to the axis of the member [reference 2, Section B].

2.2.2 Fracture

For fracture in the effective net section, the tensile fracture design strength, T_f, is the product of the fracture reduction factor, ϕ_f, and the nominal axial strength, P_{nf} [reference 2, Section D].

$$T_f = \phi_f P_{nf} = \phi_f A_e F_u \tag{2}$$

where $\phi_f = 0.75$, F_u = ultimate tensile strength, and A_e = effective cross sectional area which is defined as

$$A_e = U A_n \tag{3}$$

where U = shear lag reduction factor whose value is limited to 0.9, and it depends on the connection length and cross sectional shape; A_n = net cross sectional area which is defined as

$$A_n = A_g - n_h\left(d_b + \frac{1}{8}\right)t + \left(\sum_{i=1}^{n_d} \frac{s_i^2}{4g_i}\right)t \tag{4}$$

where n_h = number of holes in the fracture path; d_b = diameter of the bolts; t = thickness of the bolt holes; n_d = number of diagonal paths; s_i = spacing between 2 diagonal holes parallel to the loading direction of the i-th diagonal path; and g_i = gauge distance between two holes transverse to the loading of the i-th diagonal path. Both s and g are illustrated in Figure 3. Note that for staggered bolt patterns, there are more than one possible failure paths. The tensile fracture design strength is the one that has the smallest net cross sectional area.

2.3 Block Shear

Block shear is a limit state in which the resistance is determined by the sum of the shear strength on a failure path and the tensile strength on that same failure path. The design strength for block shear rupture, T_b, can be determined as follows [reference 2, Section J]:

$$T_b = \phi_b P_{nb} = \begin{cases} \phi_b \left(0.6 F_y A_{gv} + F_u A_{nt}\right) & \text{if } F_u A_{nt} \geq 0.6 F_u A_{nv} \\ \phi_b \left(0.6 F_u A_{nv} + F_y A_{gt}\right) & \text{if } 0.6 F_u A_{nv} > F_u A_{nt} \end{cases} \qquad (5)$$

where A_{gv} = gross area subject to shear; A_{nv} = net area subject to shear; A_{gt} = gross area subject to tension; and A_{nt} = net area subject to tension. For this failure mode, there are numerous possible failure paths. The design block shear rupture strength T_b is the smallest value among all the possible paths.

2.4 Limiting Design Strength

Based on the three possible failure modes, tensile yield, tensile fracture, and block shear rupture, the design strength for a given pin connected tension member can be determined. The design strength, T, for the member is the minimum value of the computed design strengths:

$$T = \min(T_t, T_f, T_b) \qquad (6)$$

3 The *Tension Connection Analyzer*

3.1 Overview

It is the intent of this program to enhance student's understanding on the response of tensile members with pinned connections through the use of computer-aided simulation. Whether the user is relatively new to the analysis of tensile members or has a working knowledge of the analytical process, the *Tension Connection Analyzer* can help improve comprehension of this topic. The program has a Windows based environment complete with toolbars, dropdown menus, and a comprehensive help file, which guides the user through a sample session. In short, the *Tension Connection Analyzer* is designed with the student in mind, and consequently contains the tools necessary to create an effective learning environment.

Since the program is intended to help students comprehend the topic of tensile member analysis, it is designed for use both inside and outside the classroom. The *Tension Connection Analyzer* has both a demonstration and an analysis mode.

Demonstration mode is intended more for the overall presentation of tensile member design strength analysis as it gives both a mathematical and an animated graphical representation of the primary failure modes. This mode allows the instructor to exhibit various bolt patterns and their animated failures rapidly and thoroughly. The animation portion of the demonstration mode shows propagation of mode failures through the connection, allowing the students to view dynamic real-time examples versus the static before and after models of the failures.

Also, the demonstration mode allows for a cost-effective method of meeting the needs of the sensing students. Previous in-class examples would have to consist of fabricated, small-scale connection systems. These systems generally can only exhibit a single failure path, thereby making it very costly to generate several examples. The *Tension Connection Analyzer* allows the instructor to show up to ten different failure paths for both fracture and block shear, for up to six different bolt patterns, for angles, channels, or W-shapes. The visualization of the failure modes and their paths is made possible through the use of the "VCR" controls.

The VCR allows for the top ten controlling failure paths for fracture and block shear to be viewed by the user. It displays the failure paths along with their corresponding failure loads. The VCR is intended to help the user get a feel for how the failure loads for different failure paths compare to one another. The user can scroll through the different paths and view the failure simulation by selecting the play button. The calculation screen accompanies the VCR. Each individual failure path on the VCR will have its own failure load. However, the calculation screen only consists of the computations for the controlling fracture and block shear paths for the chosen bolt pattern. The combination of visualization and computation was created for the sensing style student as a means of providing a concrete example. With all of the mentioned features of this mode, it can be seen that the intention of the demonstration mode is to enhance the experience of the sensing student. The focus of the analysis mode, on the other hand, is to allow all students the ability to put their understanding of the behavior of tensile members to work.

The analysis mode of the *Tension Connection Analyzer* allows for direct study of specific failure paths. This study is performed through user input of all the necessary, path-specific variables. Whereas the demonstration mode consists of both graphical and mathematical representation of the failure paths, the analysis mode only displays the computations since the user has already chosen a path. This mode presents a means by which those students with an established background in tensile member analysis can test specific paths for failure.

At first, some may view this mode of the program as a "cheat" tool for students to complete their homework. However, upon further review it can be seen that the students must have a working knowledge of all of the variables necessary to define a specific failure path. This understanding of all necessary variables is the actual focus of the topic of tensile member strength. The number crunching is strictly a formality of the analysis. Also, the analysis mode does not tell the student whether or not the chosen path controls the design, but rather only computes and displays the design strength based on the individual pathway chosen by the student. The student must then generate alternate variable values to describe various other possible failure paths in order to produce a satisfactory, realistic, and complete analysis of the system. Solutions of this type include design parameters such as: lightest cross-section, number of rows of fasteners, number of fasteners per row, and size of fasteners used in the connection. These parameters have been taken into consideration in order to complete the design experience of the *Tension Connection Analyzer*.

The *Tension Connection Analyzer* not only serves as a means to visualize and solve for tensile member behavior, but also encompasses the process of engineering design. This process includes design based on realistic specifications, restraints, and performance criteria. The specifications include all sizes of cross-sections found in the second edition of the LRFD[2] manual for angles, channels, and W-shapes. They include a choice between A36 and A572 steel for the cross-sections, and A325 and A490 steel for the bolts. Also, there is a choice of bolt diameters ranging from $\frac{1}{2}$ *in*. to $1\frac{1}{4}$*in.*, in $\frac{1}{8}$ *in.* increments, using U.S. Customary units. These parameters allow the *Tension Connection Analyzer* to act as a design tool and not just a solver. By allowing the user to choose the attributes of the connection, they must keep in mind such factors as:

- “Am I using the lightest cross-section possible to minimize cost?”
- “Should I increase the cross-sectional area or change to a stronger steel?”
- “Would adding another row of bolts be realistic or beneficial?”

All of these questions are considerations in tensile member design. Consequently, they are all included in the *Tension Connection Analyzer*. For example, as the user goes through the program he or she has the ability to choose between factors such as material strength, cross-section, and bolt size. Once the design strength for the input criteria is produced, the user can then go back through and change any desired parameters and then compare the results. For example, if a smaller cross-section were used in order to cut down on the cost of the material, would it sacrifice too much strength and become unsafe? The ability to print out any screen in the program allows for load comparisons to be made as the user changes different design parameters. For questions on how the *Tension Connection Analyzer* works there is a comprehensive on-line help file.

The help file exists not only to assist users through the program step-by-step; it also helps in communicating the language of tensile connections through definitions and explanations. The help file consists of a short summary on the foundation of tensile connections, as well as some of the ideology behind each of the modes, demonstration and analysis. It then takes the user through a sample session of the program showing screen shots for each of the interfaces that the user will be shown. The *Tension Connection Analyzer* is self-guided in that if certain parameters are not selected, the program prompts the user for the necessary details. However, if the user does not understand why a particular parameter is necessary to continue, the help file contains detailed descriptions of the requirements of each screen. Also, the help file contains a complete listing of all the variables used in the calculations, as well as their units of measure.

3.2 Highlight of User-Interface

This section summarizes the sequence of actions a user would take to view the analysis of a tensile member connection. Typical screen shots of the program are presented to facilitate the discussion. A comprehensive online help is available from the program (Office 2000 is needed for online help but not required for the execution of the program). A user can access to the help file any time he/she wishes. Williams[4] presented the entire help file in his thesis.

Once the program is installed and executed, the user would need to follow the procedures outline below to perform an analysis or see a demonstration.

- Click the “start” button on the screen to initiate the analysis.
- Choose “analysis” or “demo” mode, then click “start”.
- Choose material type and cross sectional shape by category (see Fig. 5).
- Select cross sectional size according to AISC classification (see Fig. 6).
- Select material type, shape and size for bolts (see Fig. 7).
- If “analysis mode” was chosen earlier, the user will be asked to select bolt patterns (see Fig. 8), bolt spacing, as well as information relating to the calculation of block shear (see Fig.9).
- If “demo mode” was chosen earlier, the user will be shown the screen of Fig. 10. The user only needs to input the gage length and select one of the 6 patterns shown.
- Once the information is provided, the program will perform the analysis and display either the calculation for the failure path selected (for “analysis mode” only), or it will display both the calculations for the critical path and the critical block shear failure mode (Figs. 11-14). In the “demo” mode, the user can play the “VCR” to see how a chosen failure path fails in fracture and block shear. Depending on the cross sectional shape and bolt pattern, up to 10 different failure paths are available for animated viewing.
- Finally, the user can obtain a hard copy of the calculation (both “analysis” and “demo” modes) and the image of the failure paths (“demo” mode only) by clicking the “print” button.

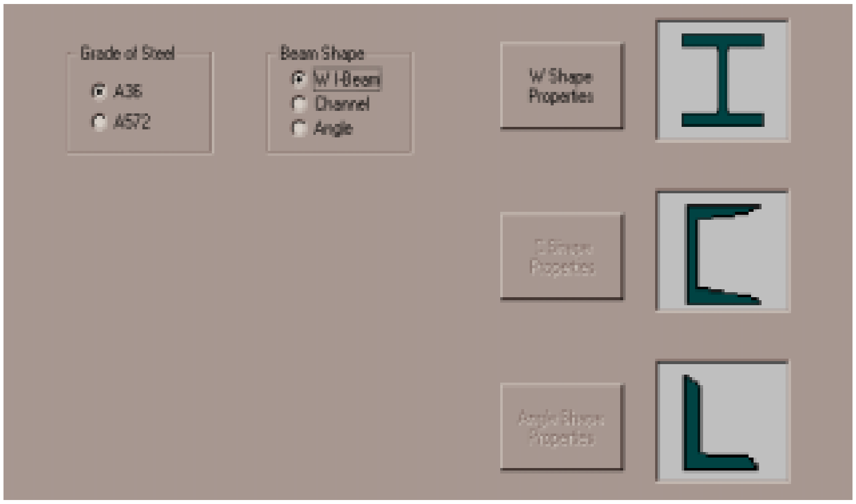

Figure 5. Steel Grade and Cross Sectional Shape Selection

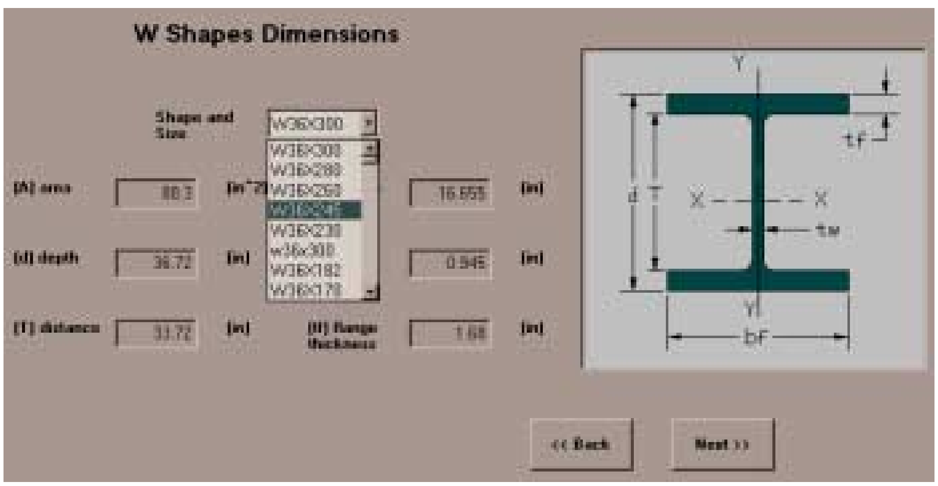

Figure 6. Example of Drop Down List of W Shape Sections.

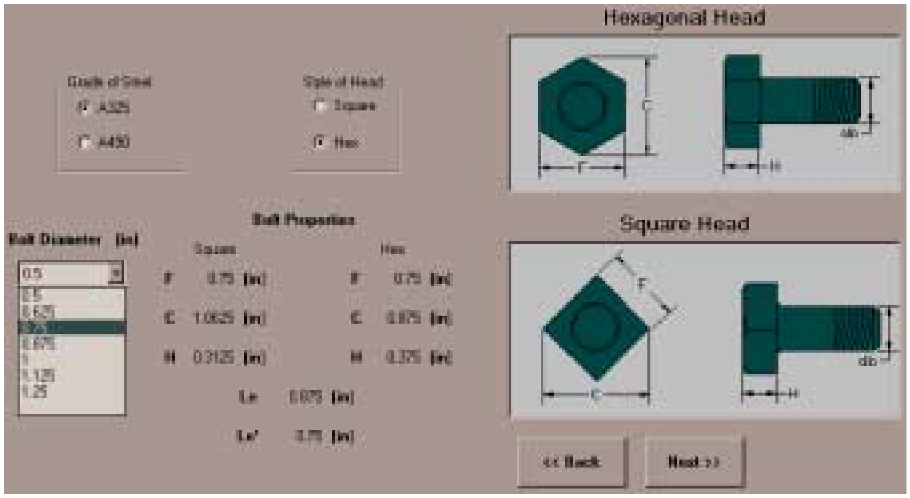

Figure 7. Bolt Properties Screen.

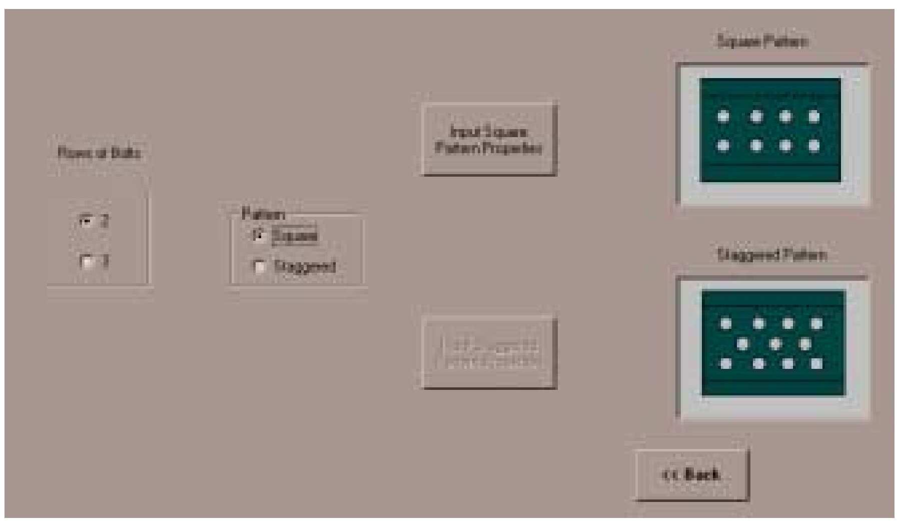

Figure 8. Bolt Pattern Selection (for "Analysis" Mode Only).

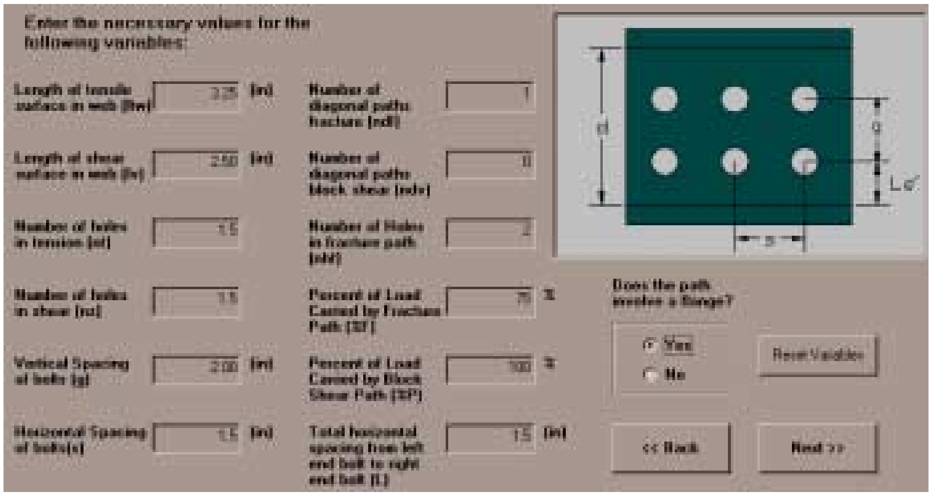

Figure 9. Input Square Pattern Variables (for "Analysis" Mode Only).

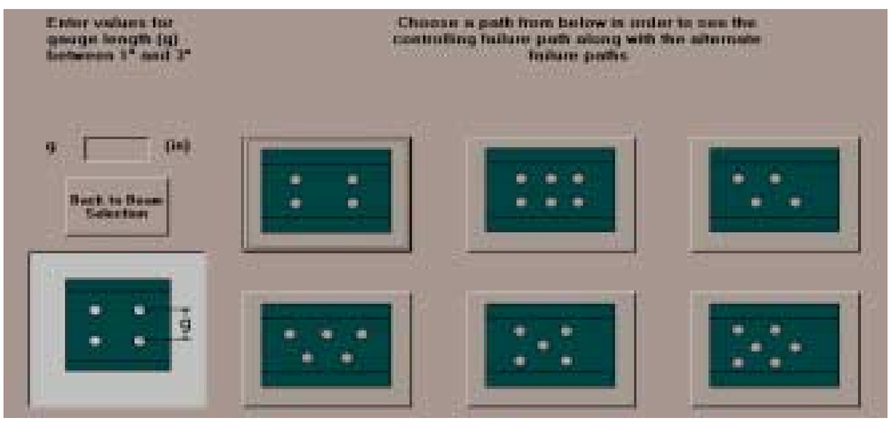

Figure 10. Bolt Pattern selection (for "Demo" Mode Only).

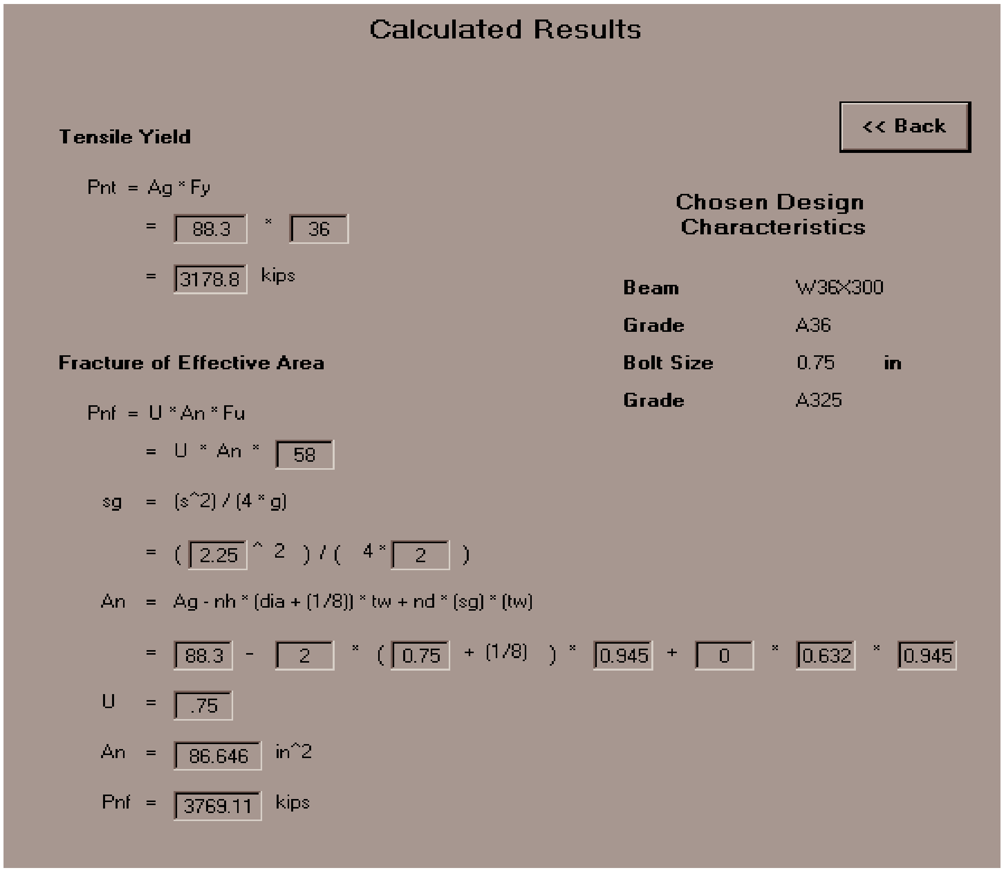

Figure 11. Top of Calculation Screen Showing Tensile Yield and Fracture Calculations.

Figure 12. Block Shear Calculation.

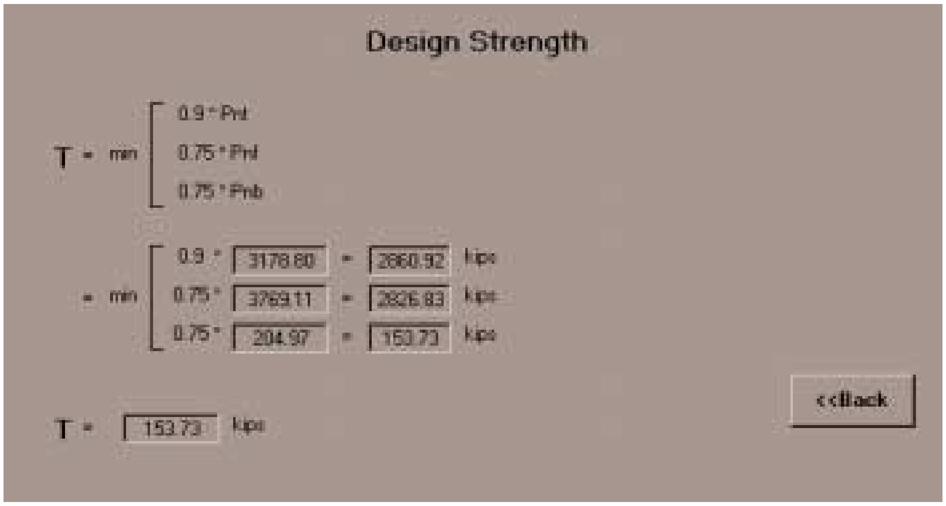

Figure 13. Design Strength Calculation.

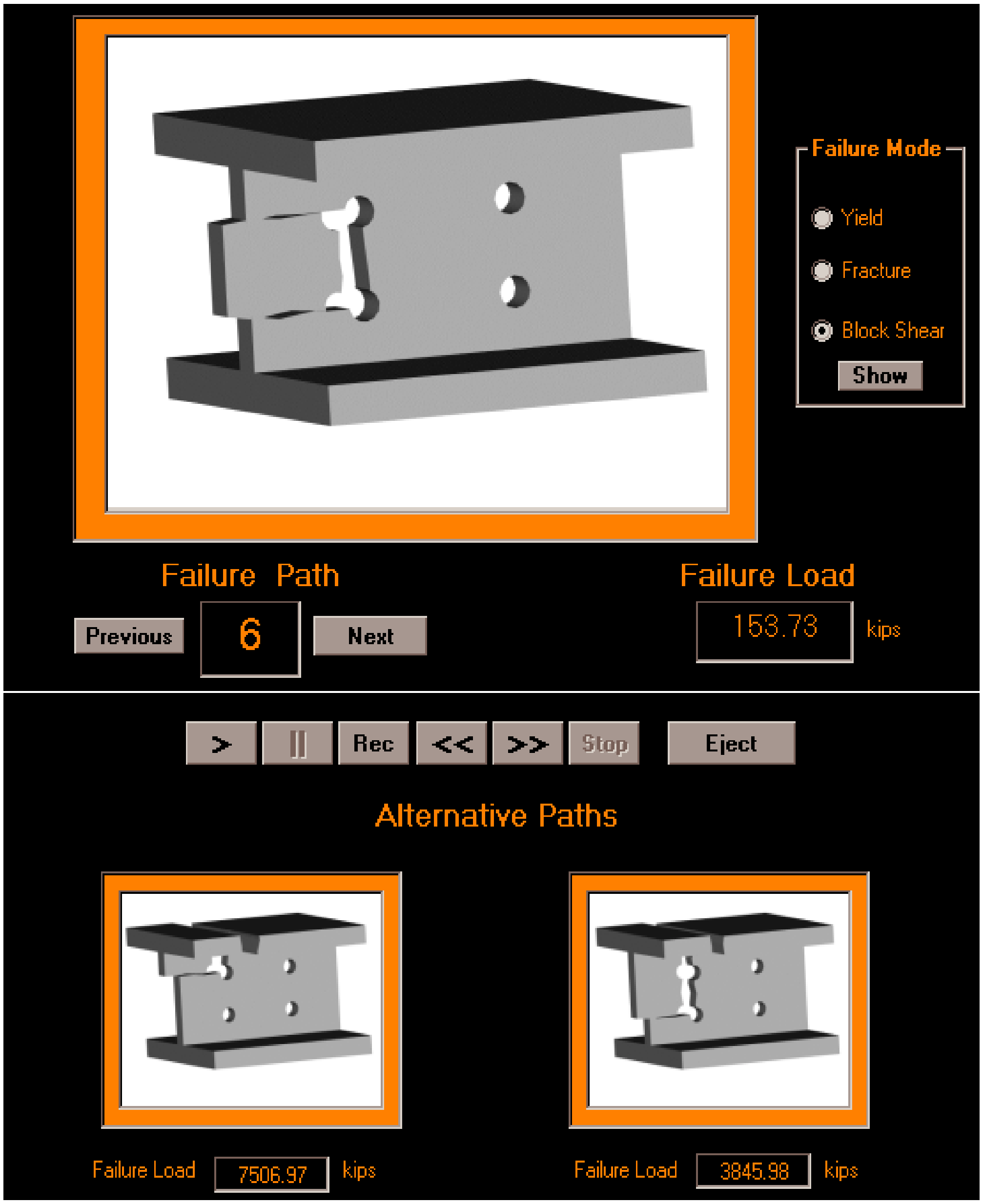

Figure 14. VCR Sample.

4. Conclusions

The *Tension Connection Analyzer* is an educational tool that serves both the instructor and the student as a supplemental device for the topic of tensile member design. With minimal in-class demonstration time, the instructor can send students home with an easy-to-use Windows based program that will help the students visualize the topic of tensile member design. Since the program has its own on-line help, the instructor can feel confident that the students will be able to quickly learn how to use the program, in order to get the most out of the program. The analysis mode of the program is intended to help the instructor save class time as it allows students the opportunity to analyze their own "what if" scenarios. Also, the animated visualizations of the *Tension Connection Analyzer* keep the instructor from having to carry around bulky demonstration models to and from class.

As for the students, they will have a program that enhances their knowledge of tensile member design without the burden of lengthy hand calculations. However, as the students become comfortable with the methodology of the tensile member design, the program can then serve as a means of checking their hand calculations. Also, with the *Tension Connection Analyzer* being so visually oriented, the students can view numerous failure paths and the corresponding failure loads, in order to more quickly get a feel as to what the "most likely" failure paths might be for different connection patterns. This ability to predict the controlling failure paths will allow the students to become more productive outside the classroom as well as on examinations.

Through all of the aspects contained in the *Tension Connection Analyzer*, it can be seen that the need for an educational media in the area of tensile connection design has been met. The *Tension Connection Analyzer* affords an instructor the comfort of sending students home with a tool that not only gives numerous samples, but also allows students to check their hand calculations. In short, instructors gain flexibility in their approach to the topic, and students of all learning styles are given the opportunity to gain competency in the topic of tensile connections.

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