Computer-Aided Design of Riveted and Bolted Joints Under Compound Loading

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ABSTRACT. An educational software called *Eccentric loading* is introduced. *Eccentric loading*, is a user-friendly and yet powerful tool for the analysis and design of riveted and bolted joints that are subjected to eccentric loads. The user starts the application by specifying his case as compound shear if the load is in the plane of the fasteners, eccentric loading if the applied load is not in the plane of the rivet or bolts, and general loading if the loading is of amore general type.

In all three cases, the user is prompted to select his objective either as Determining the factor of safety, or to find the diameter of the fastener. Fulfilling some of the objectives, further requires the description of the *Geometry* of the joint, and the specification of the *materials,* unless the use of the default material is acceptable.

Invoking next, the *Solve* command, which is equivalent to invoking the OK button, the software carries out a series of tedious computations, after which, it presents a comprehensive *Report* comprising a summary of *stresses, joint efficiency* and *factors of safety,* and a detailed summary of the *joint* geometry and properties.

1. Introduction

Riveted and bolted joints are frequently subjected to eccentric and compound loadings. In eccentrically loaded joints, the line of action of the load does not pass through the centroid of the fastener system. Consequently all elements of the fastener are not loaded equally. Eccentric loading of riveted joints causes secondary shear caused by the tendency of the load to twist the joint about the center of gravity. This is in addition to the direct or primary shear.

Results of tests on 48 T-stub specimens were presented by Swanson and Leon [1]. The main variables tested included the size of the T-stub, the gauges of the bolts, and the type and diameter of the bolts. Most of the T-stubs failed by net section fracture through the stem and by tension fracture of the bolts, but generally the failure was after significant plastification had occurred. Other failure modes observed included bolt shear and block shear. The results indicated that current design equations provide conservative estimates of the ultimate strength of the T-stubs but that they are not necessarily good predictors of the governing failure modes.

Sergeev et al [2] studied the effect of bolt spacing and degree of anisotropy on the bolt load distribution and nature of the failure mechanism. Bolt loads and failure prediction were determined using a solution method that treats the contact stresses and contact region as unknowns. Utilizing the boundary collocation technique, this method provides the non-linear solution while capturing the effects of finite geometry under general loading conditions. The nature of the failure mechanism was established by using the maximum strain criterion. Comparison of the predictions with experimental results revealed close agreement.

Ellis and Tordonato [3] reported on the development of analytical life prediction methods for high temperature turbine and valve studs/bolts. In order to validate the approach, the calculated results were compared to the results of uniaxial stress relaxation testing, bolt model testing and service experience. Long time creep, creep-rupture and stress relaxation tests were performed by the National Research Institute for Metals of Japan (NRIM) for 12Cr -1Mo -1W- 1/4V, Type 422 stainless steel bolting material, at 500C, 550C and 600C. Based on these results and limited tests for a service exposed bolt, the creep behavior was described using a two-parameter material model. For comparison with the measured uniaxial stress relaxation properties, the stress relaxation was calculated using the two-parameter creep equation and a strain hardening flow rule. The rupture time data was correlated using time-temperature parameter methods. A power law was used for the rupture strain versus rupture time relationship at each temperature. The calculated stress versus time curves were in good agreement with the measured at all temperatures and for initial strain levels of 0.10%, 0.15%, 0.20% and 0.25%.

In steel construction, sometimes bolts and welds must be combined in a single joint. Manuel and Kulak [4] observed that provisions for the design of these combination joints can be found in existing specifications, but the design rules generally have not been verified by physical tests. An experimental study using full-scale tension lap splices that combined high-strength bolts and fillet welds was carried out in order to develop a better understanding of combination joints. The results showed that the orientation of the welds and the bearing condition of the bolts are two key factors that must be considered when determining the extent of load sharing in combination joints.

De Matteis et al [5] focused on the behaviour of aluminum alloy T-stub joints. The analysis was developed by means of finite element method simulation carried out with the non-linear code ABAQUS. The analysis showed that, contrary to steel joints, the collapse mechanisms cannot be clearly defined, owing to a more gradual transition observed between each other. The authors reasoned that this is mainly a consequence of the stronger influence of the alloy hardening features.

The effect of external bending moments on the behavior of two types of ASME NPS 4 class bolted flanged joints was investigated by Marchand et al (2000). During this investigation joints with weld neck flanges and another with lap joint flanges were tested under three different initial bolt stress levels. The joint leak rate, the gasket contact stress distribution, the bolt loads, and the flange rotations were recorded as a function of the bending moment applied. The test results showed that this method gives conservative estimates that are too simplistic for accurate joint tightness calculations.

Sawa et al [6] observed that it is important to improve the sealing performance of bolted flanged joints subjected to internal pressure. Recently, bolted joints with flexible flanges of stamped steel have been used in an oil-pan structure of automobile from a lightweight viewpoint. However, it is difficult to improve the sealing performance of flexible bolted flanged joints due to the reduction of the interface pressure. The authors applied a liquid sealant to a box-shaped flexible bolted flanged joints such as oil-pan structures subjected to internal pressure in order to improve the sealing performance. In the experiments, an internal pressure when a leakage occurred was measured in the case where box-shaped bolted flanged joints in which liquid sealant was applied to the interfaces between aluminum flexible flanges (the upper) with thickness of 1 and 3 mm and the steel (aluminum) flange with 10 mm thickness (the lower) and where the bolt positions were changed. The flexible flanges were fastened by M8 bolts and nuts with an initial clamping force after being joined by the liquid sealant. In addition the bolt positions were changed. Experiments to measure a pressure when a leakage occurred were also conducted on bolted joints with asbestos gaskets. In addition, the effects of the bolt distance and bolt initial clamping force (preload) on the sealing performance were examined. The bolt distance was varied as 40, 60 and 70 mm. The experiments were also conducted on bolted joints in which similar thickness stamp steel flanges were joined. Moreover, the interface stress distribution of flexible bolted joints with liquid sealant was analyzed using finite-element method. A method for estimating a pressure when leakage of internal fluid occurs was demonstrated using the interface stress distribution and the strength of the sealant. The effects of the bolt distance, bolt positions and stiffness of flanges on the sealing performance were examined.

Gaul and Lenz [7] remarked that the nonlinear transfer behaviour of an assembled structure such as a large lightweight space structure is caused by the nonlinear influence of structural connections. Accordingly, bolted or riveted joints are the primary source of damping compared to material damping, if no special damping treatment is added to the structure. Simulation of this damping amount would be important in the design phase of a structure. Several well known lumped parameter joint models used in the past to describe the dynamic transfer behaviour of isolated joints by Coulomb friction elements are capable of describing global states of slip and stick only. The authors investigated the influence of joints by a mixed experimental and numerical strategy. A detailed Finite Element model was established to provide understanding of different slip-stick mechanisms in the contact area. An lumped parameter model was developed and identified by experimental investigations for an isolated bolted joint.

To predict the crack growth and residual strength of riveted joints subjected to widespread fatigue damage, Rahman et al [8] stressed that accurate stress and fracture analyses of corner and surface cracks at a rivet hole are needed. They presented results that focus on the calculation of stress-intensity factor (SIF) solutions for cracks at countersunk rivet holes for tension, bending, and wedge load conditions. A wide range of configuration parameters were varied, including the crack size, crack shape, crack location, and length of the straight shank hole. A finite-element-based global-intermediate-local hierarchical approach was used. The results were expressed as boundary correction factors (BCFs), which are nondimensional representations of the SIF. The BCFs were determined along the crack front in terms of the physical angle, which was measured from the inner surface of the plate to a point on the hole boundary or on the outer surface of the plate. In general, the values of BCFs increased along the crack front, moving from the inner surface of the plate toward the hole boundary or the outer surface. The values of the BCFs were highest for the crack fronts closest to the hole boundary. The trends in the solutions were the same for the three loading conditions.

According to Schaeuble and Busch [9], lightweight components from fibre reinforced plastics (FRP) and metals are often combined by riveted joints. Holes, which have therefore to be drilled into the reinforced laminates, cause a wide range of different effects on damage and failure in mechanical loaded structures. Software for the design of the joints which support the designer is actually not available, according to the authors, and it is not possible to predict by intuition the effects on the strength of a joint caused by a variation of laminat parameters or loading case. They introduced a concept for the analysis of riveted joints from FRPs. A software was developed which combines a finite element module for the general analysis of FRP-metal-joints with an interactive user interface

In what follows we present the *Eccentric Loading* software, where both riveted and bolted joints are treated under eccentric and compound loading conditions. *Eccentric Loading* is part of a larger educational software package (Bogis, et. al., [10-13]) that is being developed by the authors.

2. The Eccentric Loading Package

The software is accessed by clicking on the *Eccentric Loading* button of Fig. (1) on the main menu of *Fasteners*. As soon as the mouse contacts this button, the display of Fig. (1a) becomes visible, and the button of Fig. (1) is transformed into that of Fig. (1b).

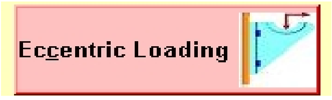


Fig. (1) : The icon for Eccentric Loading.

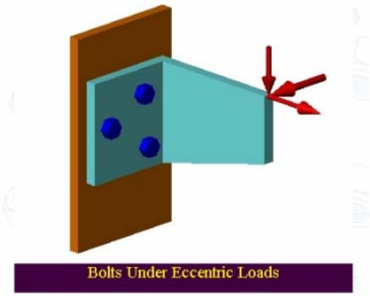


Fig. (1a) : The symbol for eccentric loading.

Fig. (1b) : Eccentric loading button during activation.

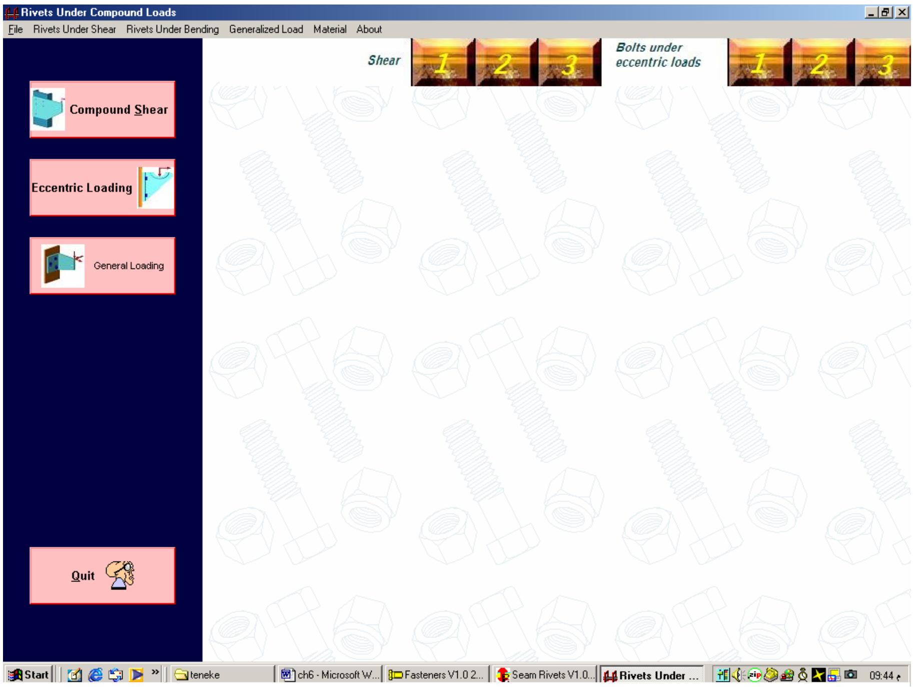


Fig. (2) : The main screen of Eccentric Loading.

Lined horizontally at the top of the mainscreen are the prompts *File, Rivets under shear, Rivets under bending, Generalized loads, Materials* and *About*. The buttons *Compound Shear, Eccentric Loading,* and *General Loading* are listed in a contact-sensitive format as separate buttons lined vertically down the left side of the screen, along with the *Quit* button.

Fig. (2a) : Choices for the layout of rivets.

When the *Compound Shear* prompt is invoked, the screen of Fig. (2a) pops up, whereby the user opts for the analysis of one of the following geometries:

1. A rectangular array of fasteners
2. A circular array, or
3. An irregular array of rivets.

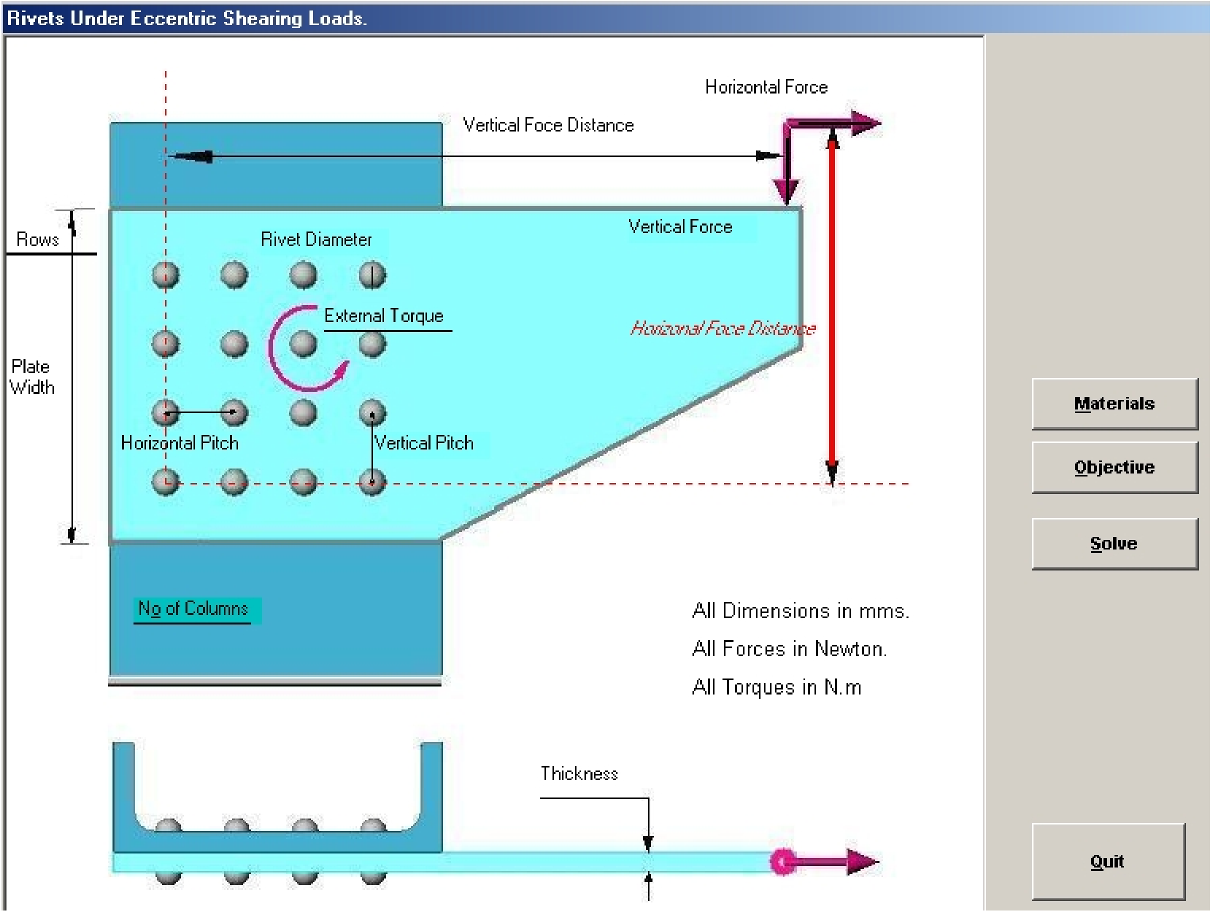


Fig. (3) : Selection of a rectangular array of fasteners.

Opting for a rectangular array, one is presented with the menu of Fig. (3). It may be pointed out that dimensions shown in Fig. (3) are contact sensitive, i.e., dimension lines and related text flicker and turn red as the pointer goes over them. The same is true about the arrows indicating forces and couples. Clicking on any of these items causes a window to be displayed for inputting of the corresponding magnitude. This is illustrated in Fig. (3a), where a window has been opened for specifying the vertical pitch of the rivets. Figures 3b and 3c show the menus that appear when the *Material* button and the Objective buttons are pressed, respectively.

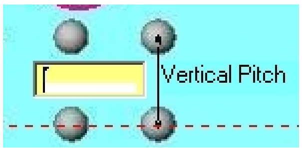
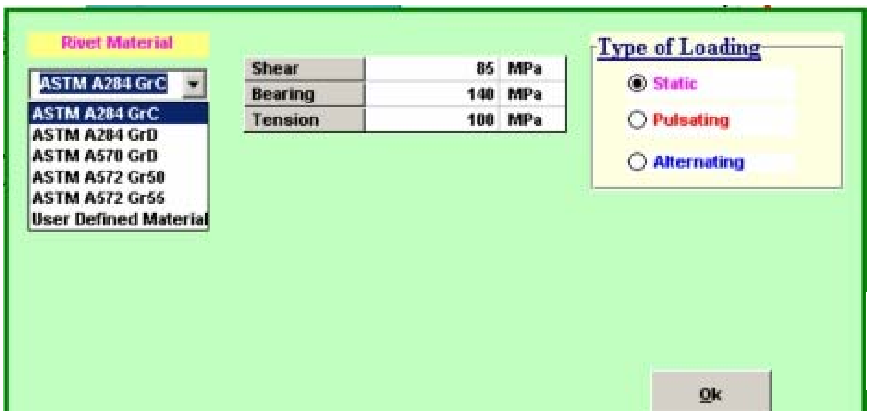


Fig. (3a) : Specification of the vertical pitch of rivets.



Shear	85	MPa
Bearing	140	MPa
Tension	100	MPa

● Static
○ Pulsating
○ Alternating

Fig. (3b) : Specification of the material for rivets.

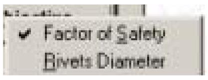
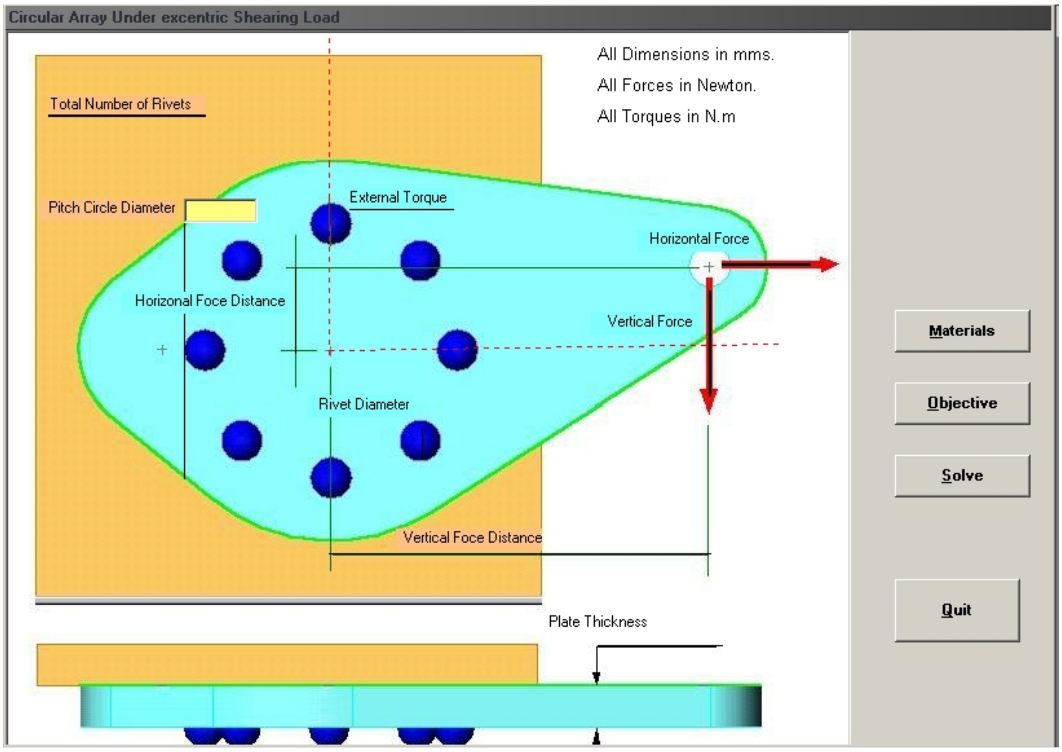


Fig. (3c) : Setting of the objective.



All Dimensions in mms.
All Forces in Newton.
All Torques in N.m

Fig. (4) : The menu for the specification of a circular pattern of rivets.

In a similar manner Fig. (4) illustrates the circular pattern that appears when the button numbered 2 is clicked next to *Shear* at the top of the menu, and Fig. (5) is displayed when button number 3 is invoked for the irregular, or user-defined option of rivet / fastener geometry.

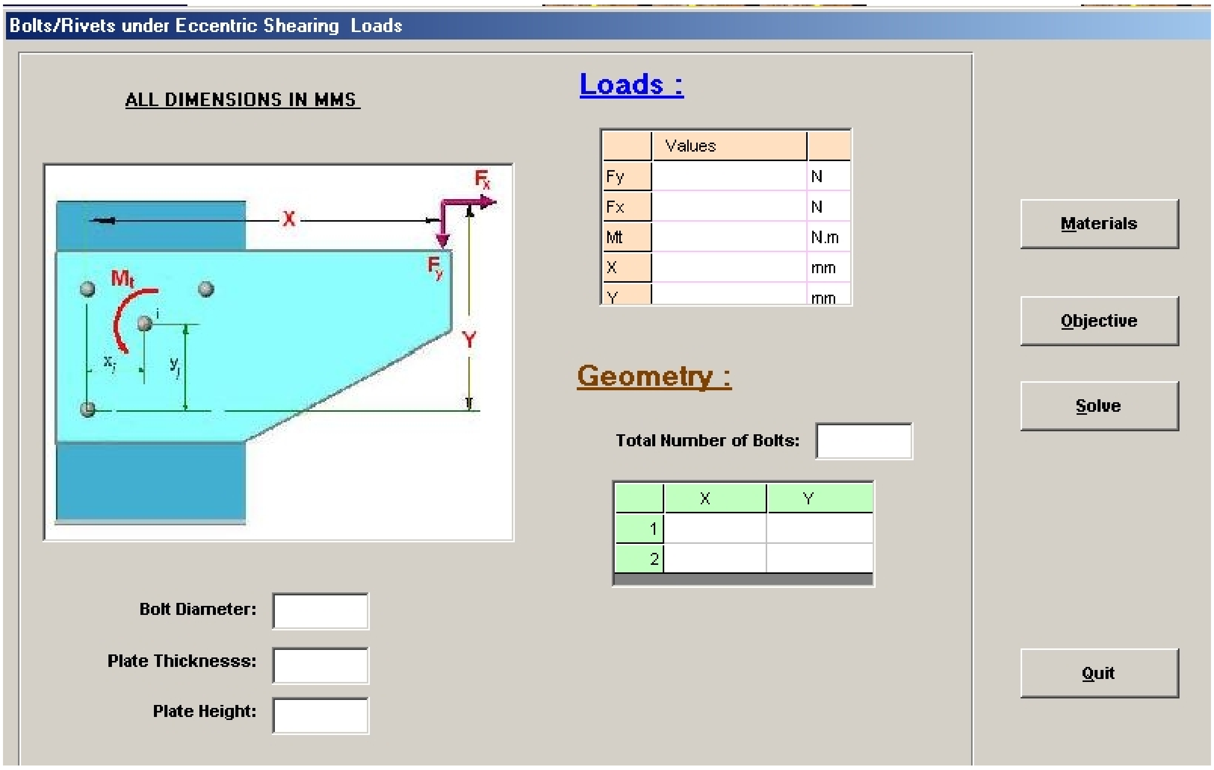


Fig. (5) : Specification of the user-defined version of rivet analysis.

In case it is desired to study a case of eccentric loading of bolts, Figs. (6) and 6a show the screens when the *Eccentric Loading* button is invoked.

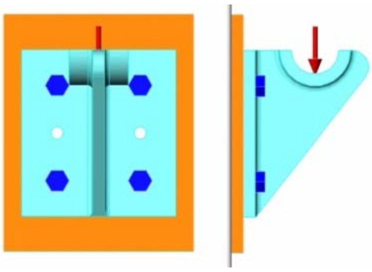


Fig. (6) : The menu during selection of eccentric loading of bolted joints.

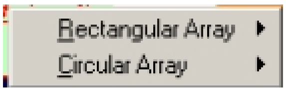


Fig. (6a) : Choices for eccentric loading of bolts.

Opting for a rectangular array, one is presented with the menus of Fig. (7) and (7a). It may be pointed out again that dimensions shown in Fig. (7a) are contact sensitive, i.e., dimension lines and related text flicker and turn red as the pointer goes over them. The same is true about the arrows indicating forces and couples. Clicking on any of these items causes a window to be displayed for inputting of the corresponding magnitude.

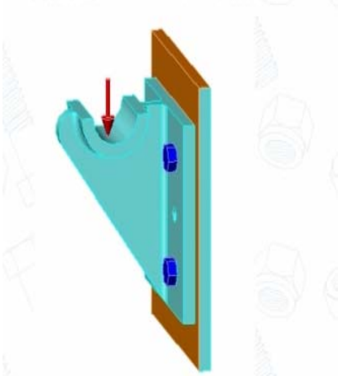
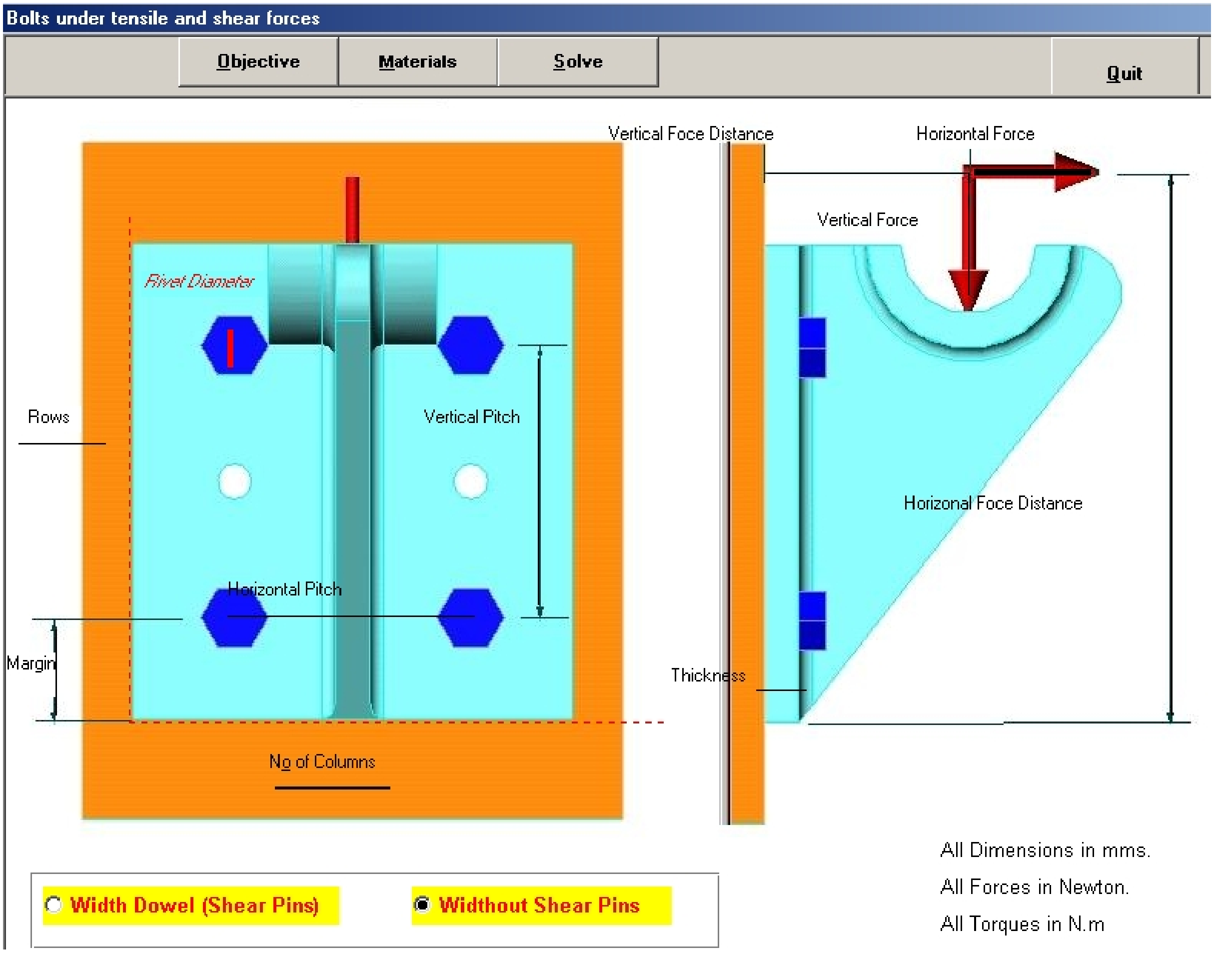


Fig. (7) : The menu during selection of a rectangular array of eccentrically loaded bolts.



○ Width Dowel (Shear Pins)

● Widthout Shear Pins

All Dimensions in mms.

All Forces in Newton.

All Torques in N.m

Fig. (7a) : Selection of a rectangular array of fasteners.

In a similar manner Figs. (8) and (8a) illustrate the circular pattern that appears when the button numbered 2 is clicked that is to the right of *Bolts under eccentric loads* at the top of the menu, and Figs. (9) and (9a) are displayed when button number 3 is invoked for the irregular, or general loading option of bolt / fastener geometry.

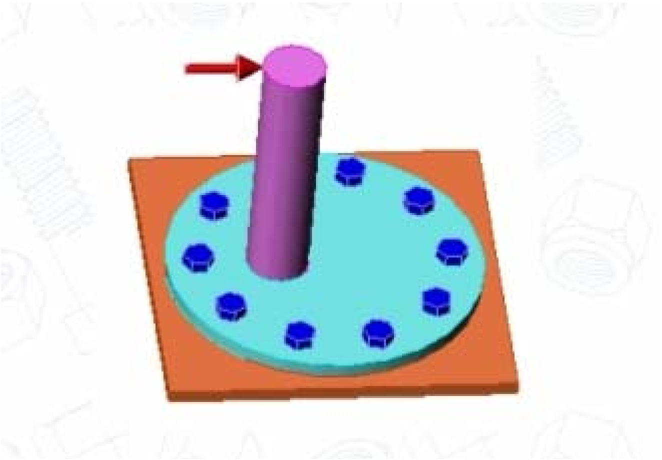
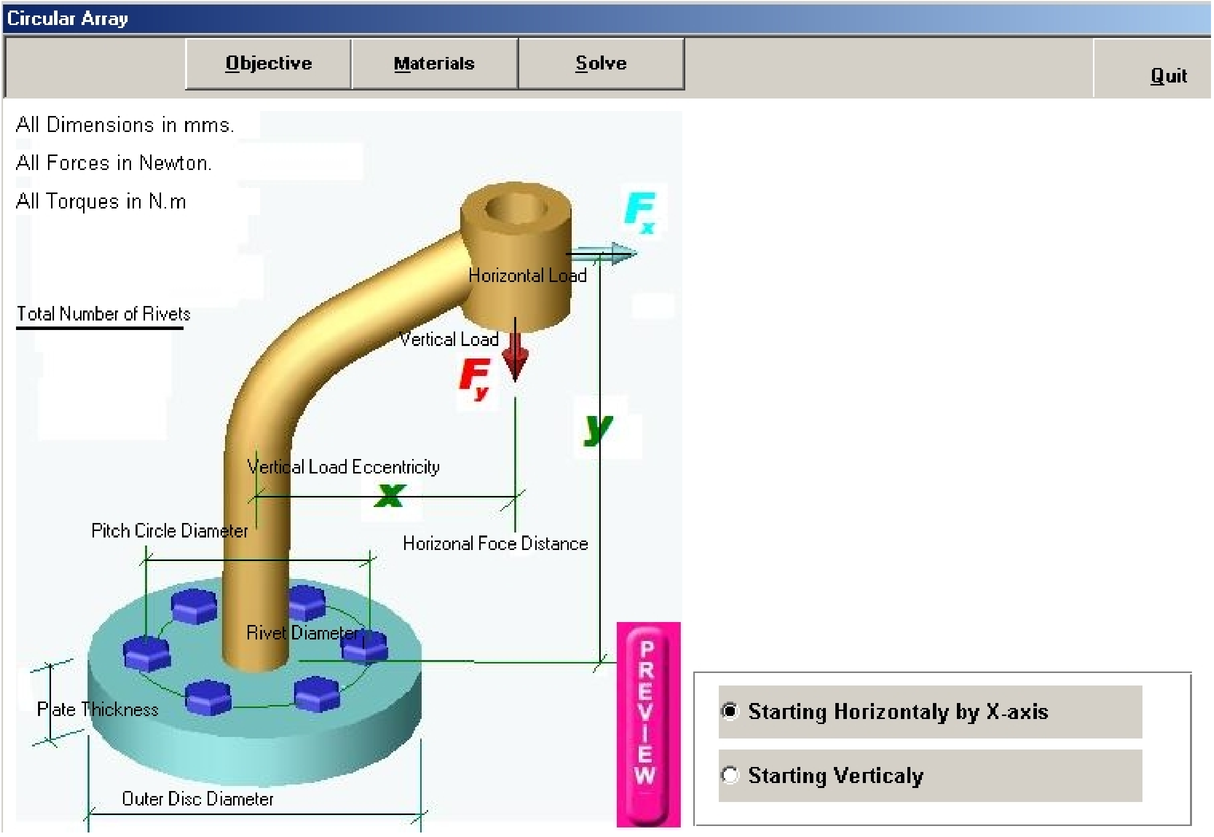


Fig. (8) : The menu during selection of a circular array of eccentrically loaded bolts.



All Dimensions in mms.

All Forces in Newton.

All Torques in N.m

● Starting Horizontaly by X-axis

○ Starting Verticaly

Fig. (8a) : The menu for the specification of a circular pattern of bolts.

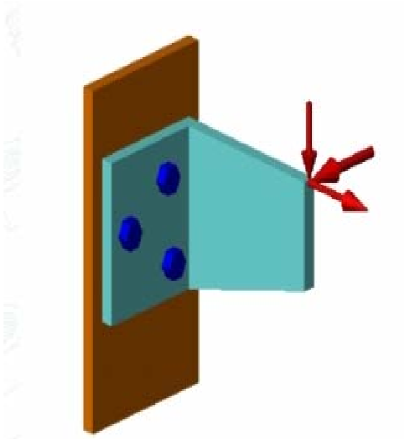
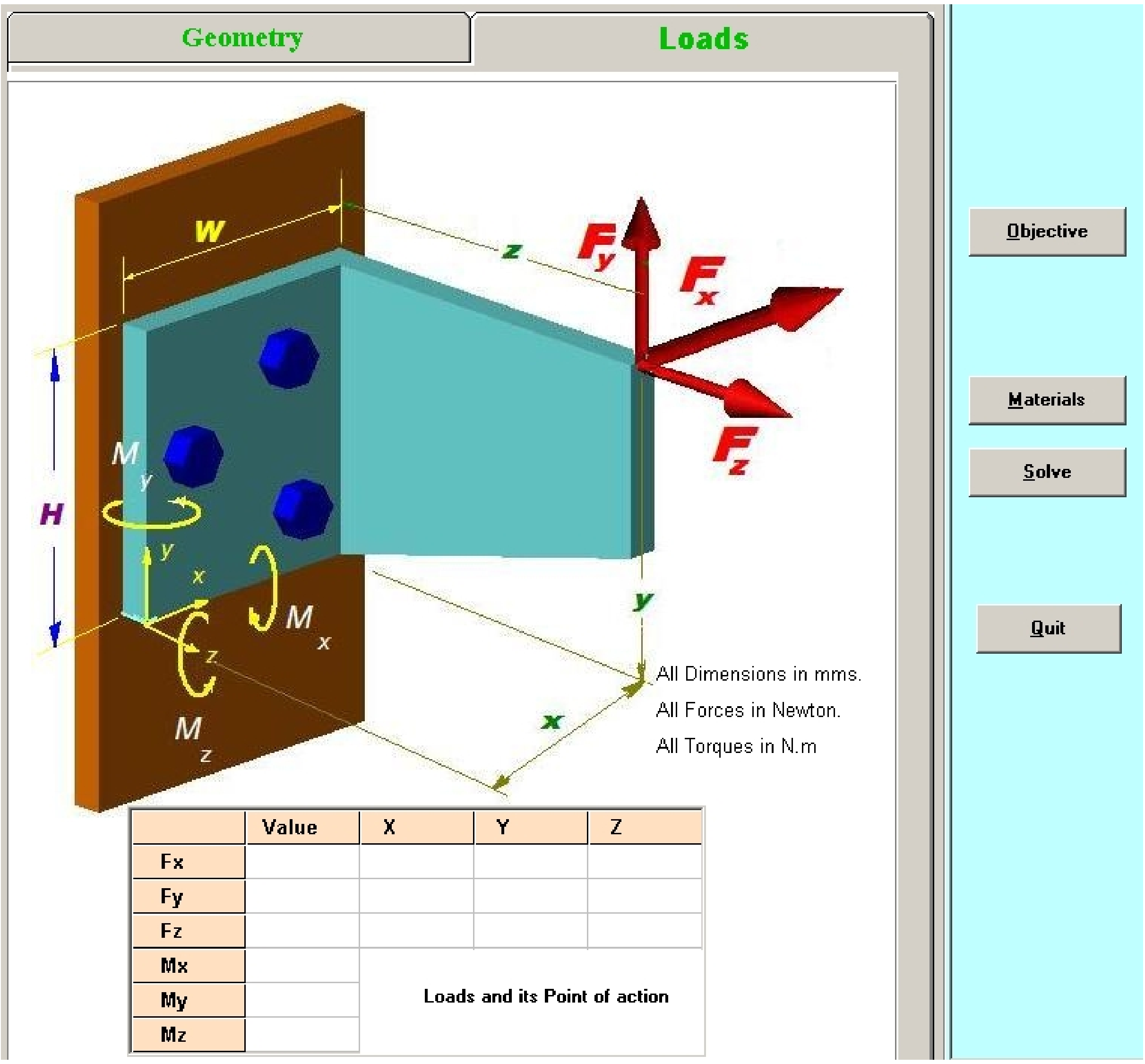


Fig. (9) : The menu during selection of a general loading of eccentrically loaded bolts.



All Dimensions in mms.

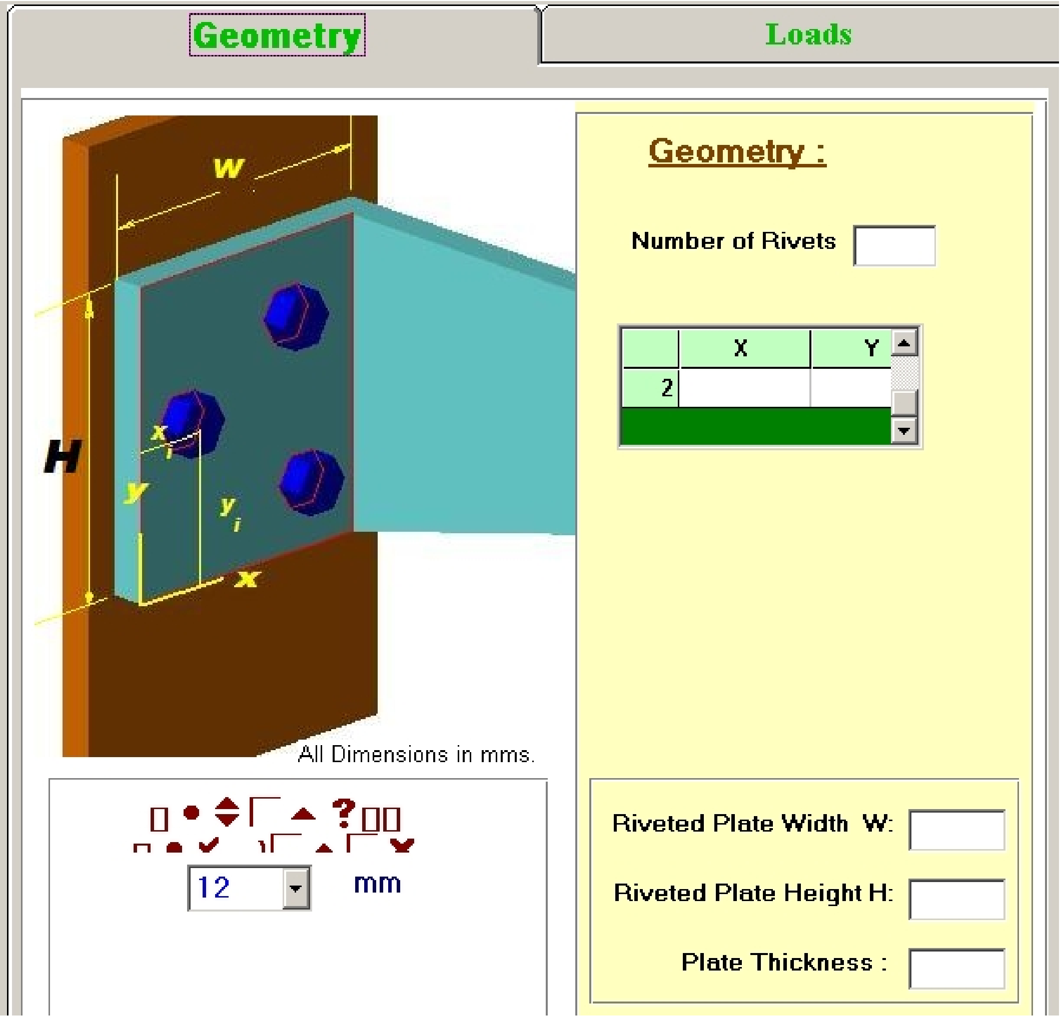
All Forces in Newton.

All Torques in N.m

	Value	X	Y	Z
Fx				
Fy				
Fz				
Mx		Loads and its Point of action		
My				
Mz				

Fig. (9a) : The menu for the specification of loading for a general pattern of bolts.

Clicking on the *Geometry* button in the menu of Fig. (9a) causes the displaying of the menu shown in Fig. (9b), where the locations of the bolts / rivets can be specified relative to a coordinate axis.



12 mm

Fig. (9b) : Specification of the locations of the fasteners.

Clicking on the *Loads* button in the same menu causes a re-displaying of the menu of Fig. (9a). The rest of the buttons have the same effects as explained above.

3. Concluding Remarks

Eccentric Loading is a user-friendly and yet powerful tool for the analysis and design of riveted and bolted joints that are subjected to eccentric loads. The user starts the application by specifying his case as one of the following.

a) Compound shear if the load is in the plane of the fasteners
b) Eccentric loading if the applied load is not in the plane of the rivets are bolts, and
c) General loading if the loading is of a more general type.

In all three cases the user is prompted to select his objective either as determining the factor of safety, or to find the diameter of the fastener. Fullfilling of some of the objectives further requires the description of the *geometry* of the joint, and the specification of the *materials* unless the use of the default material is acceptable.

Invoking next the *Solve* command, which is equivalent to invoking the OK button, the software carries out a series of tedious computations, after which it presents a comprehensive *Report* comprising a summary of *stresses*, *joint efficiency* and *factors of safety,* and a detailed summary of the *joint geometry and properties*.

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دراسة وصلات البرشام والمسامير والمعرضة لأحمال مركبة باستخدام الحاسوب

هيثم عبدالله بوقس ، على أبوالعز ، عبدالملك علي الجنيدي ، محمد أكيورت

كلية الهندسة ، جامعة الملك عبدالعزيز ، جدة

المستخلص. برنامج تعليمي لتحليل وتصميم الوصلات الميكانيكية المتصلة بالمسامير أو البرشام والتي تتعرض لأنواع مختلفة من الأحمال سواء قوى أو عزوم حول جميع المحاور.

يبدأ التطبيق بتحديد المستخدم لحالة تحميل الوصلة سواء كانت القوى و العزوم تؤدي إلي إجهادات قص فقط عمودياً على محور الوصلة، أو كان التحميل في المستوى الموازي لها، أو أن التحميل يشمل كل مستويات الوصلة. وفي جميع الحالات الثلاث، فإن البرنامج يستطيع أن يمدّ المستخدم بمعامل الأمان في تصميم الوصلة، أو حساب القطر المناسب للمسامير أو البرشام. وعلى هذا، فإن على المستخدم تقديم الأبعاد اللازمة وكذا توصيف خامات البرشام. باستدعاء أيقونة الحل، فإن البرنامج ينفذ سلسلة من الحسابات اللازمة، ومن ثم، يقدم بعدها تقريراً تفصيلياً عن كفاءة الوصلة ومعامل الأمان في تصميمها، بالإضافة إلى خواصها وأبعادها الهندسية.