Evaluation of stress distribution in bolted steel angles under tension

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ABSTRACT

The stress distribution in the vicinity of connections in a bolted steel angle is non-uniform because of the coupled effects of connection eccentricity, shear lag and stress concentrations. Although, some researchers have attempted finite element analysis, stipulations in various codes and specifications regarding the design of angle tension members are primarily based on the experimental studies. Only a couple of previous studies has included geometric as well as material non-linear effects in such finite element analysis. This paper presents the state-of-the-art review of finite element techniques used in modelling the angle tension members with bolted connections. This review is followed by a non-linear finite element analysis so as to obtain the stress distributions in the vicinity of connections, at design loads. This stress distribution is then evaluated to draw several realistic conclusions.

KEYWORDS

Connection eccentricity, shear lag, non-linear finite element analysis.

1 Introduction

Steel tension members are probably the most common and efficient members in structural applications. Steel angles are frequently used as tension members in a majority of these applications. It is relatively easy to fabricate and erect structures, or a part thereof, comprising of angles because of the basic simplicity of its cross-section. Often, it is not practicable to connect both the legs of the angle with the gusset plate. Angles are generally used as single or as a pair, symmetrically placed about a gusset plate that passes between them.

The connection between the angle and gusset may be made by welding or by bolting. Angles with bolted connections normally observe net section failure for relatively longer connections. However, for relatively shorter connections, the mode of failure may be block shear, wherein a ‘block’ of the connected element may separate from the remainder of the element. In limit state design, in addition to net section failure and block shear failure, yielding of the gross section must also be considered, so as to prevent excessive deformation of the member. The lower of these three strengths governs the maximum load carrying capacity of angles in tension.

The efficiency of angle tension members is reduced due to the coupled effects of connection eccentricity, stress concentration and shear lag. It is difficult to determine the relative participation of each of these components. The stresses are said to lag in the elements not connected directly and this is commonly referred as shear lag effect. This results in a non-uniform stress distribution across the cross-section. An accurate estimation of this non-uniform stress distribution is necessary for determination of load carrying capacity of angles under tension, which often is not possible. The efficiency of double angle tension members connected on the opposite sides of gusset is also reduced on account of this non-uniform stress distribution, in spite of non-eccentric connection. This non-uniform stress distribution across the cross-section of the ngle connected by only one leg to the gusset is shown in Figure 1.

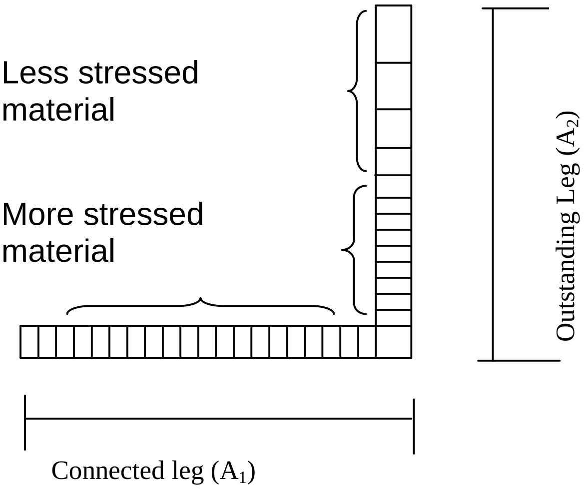

Figure 1: Non-Uniform stress distribution in angles.

The concept of effective net area has been traditionally used to account for this non-uniform stress distribution (Figure 2). The load is considered to act axially over an empirically reduced net area, called as effective area. At the time of net section failure, the stress in the connected leg can be taken to be equal to the ultimate stress, while the average stress in the unconnected leg is only a fraction of the ultimate stress. This is the essence of the failure mechanism observed during the experiments on the net section failure of angles under tension. The major factors upon which this effective area depends upon are length of the connection, distribution of area in the connection, and method of hole manufacture.

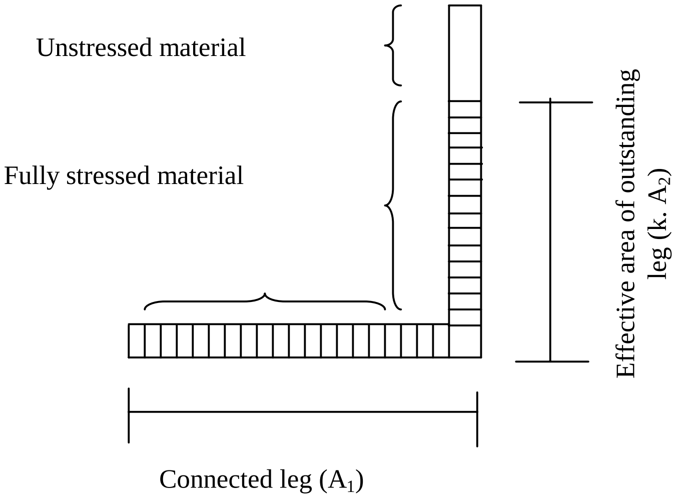

Figure 2: Concept of effective area.

The failure mode by ‘block shear’ has not yet been fully understood. The design rules in various codes base block shear failure calculation on a combination of yield and rupture strength of the net or gross areas in shear and tension on the potential failure plane. The current provisions for net section and block shear failure, in codes of most countries are primarily based on experimental studies, although some researchers have attempted finite element analysis. This paper presents the state-of-the-art review of finite element techniques used in modelling the angle tension members with bolted connections. This review is followed by a non-linear finite element analysis so as to obtain the stress distributions in the vicinity of connections, at design loads. This stress distribution is then evaluated to draw several realistic conclusions.

2 Previous work

In the past, finite element analysis of tension members had been performed with increasing degree of complexity, ranging from simple linear elastic analysis to large deformation geometric and material non-linear analysis. Linear elastic analysis can predict the stress flow in the member prior to yielding and stress re-distribution after yielding is not captured. Finite element analyses that include material and geometric non-linearities have been successful in predicting the failure capacities of tension members with varying degrees of accuracy. Following is a brief summary of the finite element modelling studies used to estimate the failure loads of connections subjected to block shear and net section rupture.

Ricles and Yura [1] conducted full-scale testing of coped and un-coped double row bolted-web connections supplemented by an elastic finite element analysis The main objective of this analysis was to obtain elastic stress distributions in the vicinity of bolt holes and to develop a modified block shear failure model which is in close agreement with the experimental results. The beam and the connection were assumed to be in a plane stress condition. The finite element model consists of two dimensional four-node quadrilateral and three node triangular elements. The material response was modelled by an elastic stress–strain curve.

Wu and Kulak [2] conducted a large experimental investigation of single and double angle tension members to examine the effect of shear lag on net section rupture of the cross-sections. Subsequently, finite element analysis was employed to evaluate the stress distribution of the critical cross- section at ultimate load. A large strain four-node quadrilateral shell element with six degrees of freedom per node was used in the finite element modelling of the angle sections. The gusset plate is modelled using elastic four-node quadrilateral shell element as yielding of the gusset plate was not observed in the experimental tests. An elasto-plastic Von Mises yield criterion is adopted to represent the material non-linear effects. The material stress–strain curve is described by a multi-linear isotropic hardening behaviour. Based on the symmetry considerations of the specimen, only half the length of the specimen is modelled. Similarly, due to the symmetry of the double angle members about the gusset plate, only one of the pair angles is modelled. In the finite element model, the effect of bolts is modelled by coupling the longitudinal and in-plane transverse degrees of freedom of the nodes attached to the hole surfaces on which the bolts bear against during deformation. The finite element model included both geometric as well as material non-linear effects. In the analysis, the failure load of the angle section was taken as the load corresponding to the last converged load step. At failure, significant necking of the net area between the leg edge and lead bolthole was observed.

An extensive finite element study was conducted by Epstein and Chamarajanagar [3] to capture the influence of bolt stagger spacing and shear lag effects on block shear failure of angles in tension. A 20-node brick element is used in the finite element modelling of the angle sections to capture the stress concentration effects in the vicinity of boltholes. The material non-linear effects were modelled using the Von Mises yield criterion and the material stress–strain curve is assumed to be elastic–perfectly plastic. In this study, a strain based failure criterion in which failure is assumed to have occurred once the maximum strain reached five times the initial yield strain was employed to capture the failure load. Further, in the finite element model, the bolts were assumed to be rigid and the load is transferred from the gusset plate to the angle fully by the bearing of the bolts. Therefore, the longitudinal and the in-plane transverse displacements of the nodes attached to the bearing surfaces, i.e. the surfaces on which the bolt surface bears against the hole surfaces are coupled to one another. This finite element study included only the material non-linear effects and the geometric non-linear effects were considered to be negligible.

Barth, Orbison and Nukala [4] conducted finite element analysis of the experimental WT section specimens. The main objective of this FEA is not only to estimate the failure loads of the WT section specimens but also to trace the entire load versus deflection path. The FEA is performed using 3D solid elements that are capable of representing large deformation geometric and material non-linearities. Finite element analysis of the WT sections is carried out using eight node incompatible hexahedral elements that are capable of representing large deformation geometric and material non-linearities. An elasto-plastic Von Mises yield criterion combined with a tri-linear true stress–true strain curve is used to represent the material non-linear effects. Based on the symmetry considerations of the specimen, only half the length of the specimen is modelled. Similarly, due to the symmetry of the WT sections about the mid-surface of the web, only half of the WT section is modelled. The leading edge of the gusset plate is constrained in all the directions except for the longitudinal direction. A longitudinal displacement boundary condition is applied at the leading edge of the gusset plate. In the finite element model, the connecting bolts are assumed to be rigid and a surface-to-surface contact is used to fully transfer the load from the gusset plate to the web. That is, a surface-to-surface contact option is used between the bolt's outer surface and the inner surface of the web holes. Additionally, a surface contact option is also used between the bolt's outer surface and the inside surface of the gusset plate holes. Similarly, a surface contact option is applied between the bottom surface of the gusset plate and the top surface of the web in order to avoid gap between the gusset plate and the web. The nodes around the boltholes on the outer side of the gusset plate are constrained in the direction normal to the web to simulate the effect of the head of the bolt. To accurately capture the stress behaviour in the region around the boltholes where it is most likely that failures would probably initiate, a mapped meshing is done around the holes. The Newton–Raphson method is used to trace the non-linear load–deflection curve beyond the load limit point. The load corresponding to the load limit point is taken as the failure load of the WT specimen. At failure, a substantial amount of necking of the net area is observed between the web edge and the lead bolthole.

3 Considerations in non-linear finite element analysis

In almost all of the relevant previous research, finite element studies are used in conjunction with an experimental testing program. The behaviour observed during the tests is used for preparing a finite element model, particularly during the non-linear analysis. In angles under tension, the behaviour is highly non-linear as the failure approaches. The finite element numerical values for failure loads may be considered reliable only when this highly non-linear nature of failure is modelled accurately. This is not that easy, as it may not be possible to capture each and every aspect of non-linear behaviour. In the following, certain aspects where due consideration is required for non-linear finite element analysis are discussed.

The behaviour of the finite element model in the non-linear range depends upon the way the material non-linear effects are represented. An elasto-plastic Von Mises yield criterion was adopted by Wu and Kulak [2] to represent the material non-linear effects. These effects were modelled by Epstein and Chamarajanagar [3] using Von Mises yield criteria and the material stress–strain curve was assumed to be elastic–perfectly plastic. The material stress–strain curve is described by a multi-linear isotropic hardening behaviour. Barth, Orbison and Nukala [4] have used an elasto-plastic Von Mises yield criterion combined with a tri-linear true stress–true strain curve is used to represent the material non-linear effects.

The interaction between the gusset plate and the angle has to be modelled accurately. As observed in the experimental program, the angle separated from the gusset plate in certain regions while there was no separation in certain other regions. While modelling, this fact must be considered and the appropriate degrees of freedom must be coupled between the corresponding nodes of the angle and the gusset plate. The region where separation occurs and where there is no separation varies from connection to connection, and it is difficult to truly translate this effect into the finite element model. The interaction between the bolt and the boltholes and its effect on the failure load must also be dealt with. Most of the previous studies do not actually model bolts, instead the degrees of freedom around the boltholes are appropriately coupled to imitate the interaction between the bolt and boltholes. This certainly introduces an unknown amount of approximation in the finite element analysis.

An appropriate failure criterion must be selected so as to ascertain the failure load. In one of the previous research, a strain based failure criterion in which failure is assumed to have occurred once the maximum strain reached five times the initial yield strain was employed to capture the failure load. In another previous research, the failure load of the angle section was taken as the load corresponding to the last converged load step. Failure criterion adopted in the previous studies does not include the effects of triaxiality and deformation gradients in the vicinity of the hole.

The method of forming the holes (punching or drilling) also influences the failure load to a certain extent. However, it is rather difficult to include such effects in finite element analysis.

4 Non-linear finite element analysis

By providing an appropriate margin of safety over failure loads, design loads are obtained. At design loads, the stresses in hole of the angle section are well below the ultimate stress. However, the stresses at design loads exceed the yield stress in certain regions. Although some information regarding the location of regions of high stress (stress concentration) can be obtained from a linear elastic analysis, substantial redistribution of stress occurs once the material yields. Therefore, it is preferable to use a non-linear analysis procedure that considers both material and geometrical non-linearities, since at design load, the connection specimen should experience strong material non-linearity in the vicinity of connection and possible geometric non-linearity as well. Accordingly, both these forms of non-linearities are considered in this study. The problems such as the failure criteria and the interaction between the gusset plate and the angle are not to be considered, if the analysis is performed at design loads. This eliminates major approximations from the non-linear finite element analysis.

Here, the main goal of the finite element analysis is to evaluate the stress distribution in the angle at design loads predicted by equations developed earlier on the basis of experimental results in a study by Gupta and Gupta [5]. Detailed finite element analysis is conducted on three bolted angle specimens tested as part of that study. These angles are 65 mm x 65 mm x 6 mm, having a specified minimum yield and ultimate stress of 250 N/mm^2 and 410 N/mm^2 respectively. These three angle specimens had two, three and four bolts at each end respectively. Since the thickness of the angles and gusset plates used are all less than one inch, shell elements are used to represent all of the connection and member components. This permits a substantial saving in computing time when compared to using solid elements as required for certain other large connection specimens.

A versatile finite element software is used to perform the analysis. A plastic quadrilateral shell element is used to model the angles and gusset plates. This element has six degrees of freedom at each of the four nodes. Yielding is determined using the Von Mises yield criteria. A representative finite element model of an angle having two boltholes is shown in Figure 3.

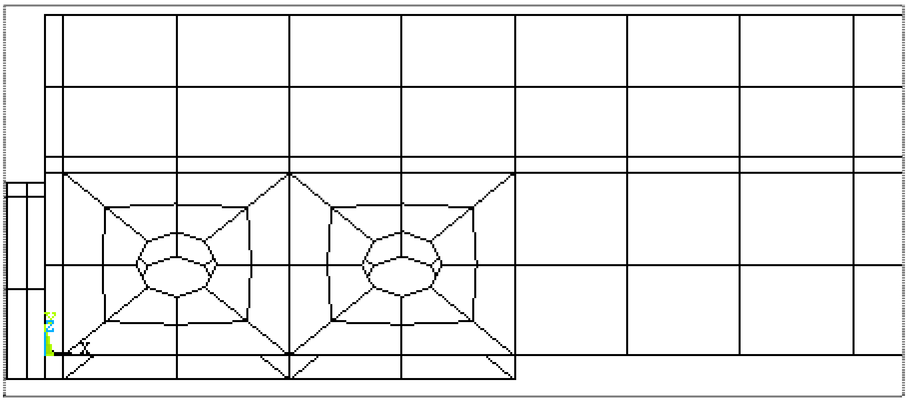

Figure 3. A representative finite element model having two boltholes.

Based on the symmetry considerations of the specimen, only half the length of the specimen is modelled. At the mid length cross section of the member, the x-direction translation degrees of freedom and the y and z direction rotational degrees of freedom are fixed. At the leading edge of the gusset plate, all the degrees of freedom are restrained except the x displacements. The effects of bolts in the finite element model is modelled by coupling one half of the circumference of each bolt hole in the angle, which is supposed to bear against the bolts in the tests, with the opposite face of the corresponding bolt hole on the gusset plate for the x and y translation degrees of freedom. This is done node by node. Additionally, all nodes around the boltholes of the angle are coupled with the corresponding nodes of the gusset plate for the z translation degrees of freedom.

5 Results and discussion

Figures 4a, 4b and 4c shows the stress distributions in the angle section at design loads (108.44 KN), when there are two bolts in the connection. Figure 4a shows the SX stresses, Figure 4b shows the SXY stresses and Figure 4c shows the SVM (Von Mises) stresses. The angle section and connection geometry is same as for the specimen 65_2_1a. Figures 5a, 5b and 5c shows the stress distributions in the angle section at design loads (144.44 KN), when there are three bolts in the connection. Figure 5a shows the SX stresses, Figure 5b shows the SXY stresses and Figure 5c shows the SVM (Von Mises) stresses. The angle section and connection geometry is same as for the specimen 65_3_1. Figures 6a, 6b and 6c shows the stress distributions in the angle section at design loads (144.44 KN), when there are four bolts in the connection. Figure 6a shows the SX stresses, Figure 6b shows the SXY stresses and Figure 6c shows the SVM (Von Mises) stresses. The angle section and connection geometry is same as for the specimen 65_4_1.

Maximum SX stresses in three bolts (Figure 5a) and four bolts (Figure 6a) connection are around 350 N/mm^2. In case of two bolts (Figure 4a) connection, maximum SX stresses are around 300 N/mm^2 only. This indicates a comparatively conservative prediction of design loads in case of two bolts connection as compared to three and four bolts connection. It is recalled that that the block shear strength governed the design in two bolts connection. The professional factor (defined as ratio of experimental failure load to the predicted load) for this angle is obtained as 1.11, while the professional factors of three and four bolts angles are around 1.00. That is, the block shear strength predictions are somewhat conservative than the net section strength predictions. It is because of this reason that the maximum stresses are comparatively low in a two bolts connection. The experimental results are very well reflected by the finite element analysis.

In three bolts and four bolts connections, the zones of high SX stresses lie primarily along the critical section in the connected and un-connected legs. In a two bolts connection, the SX stresses are mainly concentrated on the connected leg only, and in the un-connected leg, the stresses are relatively low. However, in all three cases, these stresses are well below the ultimate stresses, suggesting ample factor of safety and safe prediction of design loads by the equations developed earlier on the basis of experimental results.

It is observed that the magnitude and distribution of stresses at critical section for three bolts and four bolts connection is almost same. This is in line with the finding that one provision should be made for three or more bolts.

In Figures 4b, 5b and 6b, SXY stresses are plotted. From these figures, it is seen that the stresses are mainly concentrated along the gross shear plane in all the three connections. This justifies the use of area along gross shear plane in block shear strength prediction equation. The gross shear plane is lightly stresses in four bolts connection, while it is relatively more stressed in three and four bolts connection. However, in a two bolts connection, the stresses extend up to the end of the specimen. It seems that the failure path will divert along the gross shear plane in this connection, looking to the large concentration of stresses near the lead bolthole.

In Figures 4c, 5c and 6c, the Von Mises stresses are plotted. The distribution and concentration of these stresses indicates that block shear failure may occur in a two bolts connection, and net section failure may occur in three and four bolts connection. This is line with the experimentally observed failure modes.

6 Concluding Remarks

Finite element analysis can certainly be used to analyze angles with bolted connections, giving due considerations to associated problems such as the shape of the material stress-strain curve, the contact between the gusset plate and the angle, the appropriate failure criteria, the effect of punching of holes etc. The problems such as the failure criteria and the interaction between the gusset plate and the angle are not to be considered, if the analysis is performed at design loads. This eliminates major approximations from the non-linear finite element analysis. Moreover, the time required for time needed for computations is also reduced and the resulting stress distributions can be used confidently for ascertaining the adequacy of equations developed on the basis of experimental results. The following main points, in relation with stress distribution, are noted:

- In three bolts and four bolts connections, the zones of high SX stresses lie primarily along the critical section in the connected and un-connected legs.
- In a two bolts connection, the SX stresses are mainly concentrated on the connected leg only, and in the un-connected leg, the stresses are relatively low.
- The magnitude and distribution of stresses at critical section for three bolts and four bolts connection is almost same.
- The resulting stresses distribution justifies the use of area along gross shear plane in block shear strength prediction equation.
- The distribution and concentration of Von Mises stresses indicates that block shear failure may occur in a two bolts connection, and net section failure may occur in three and four bolts connection.

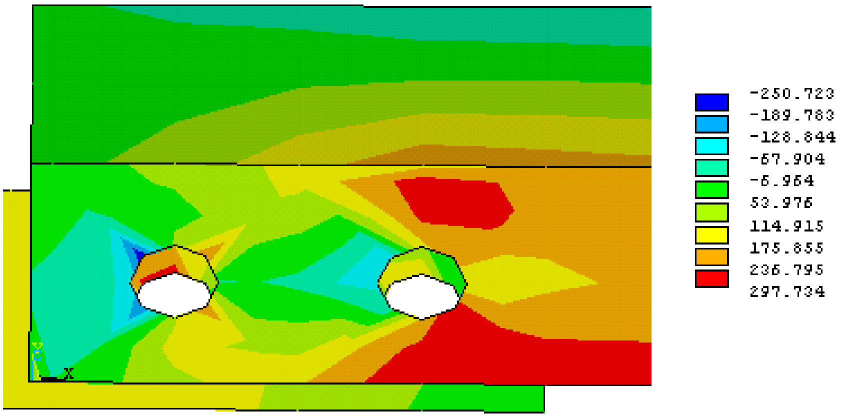

Figure 4a: SX stresses for two bolts at design loads.

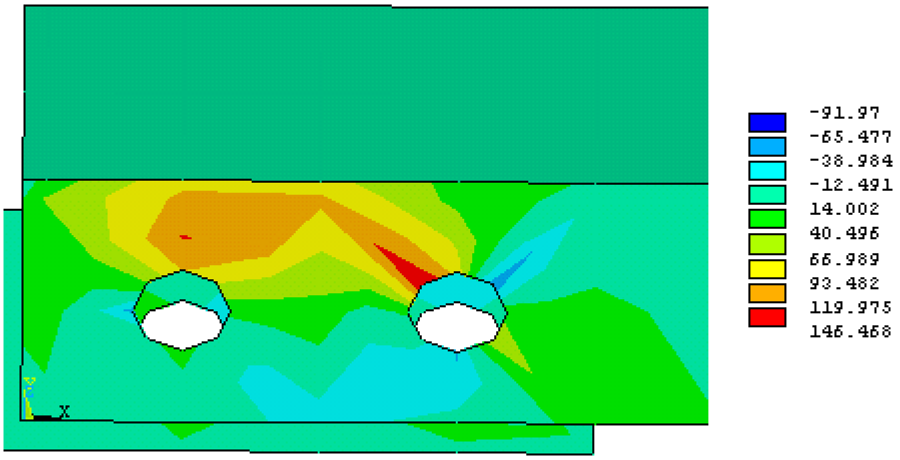

Figure 4b: SXY stresses for two bolts at design loads.

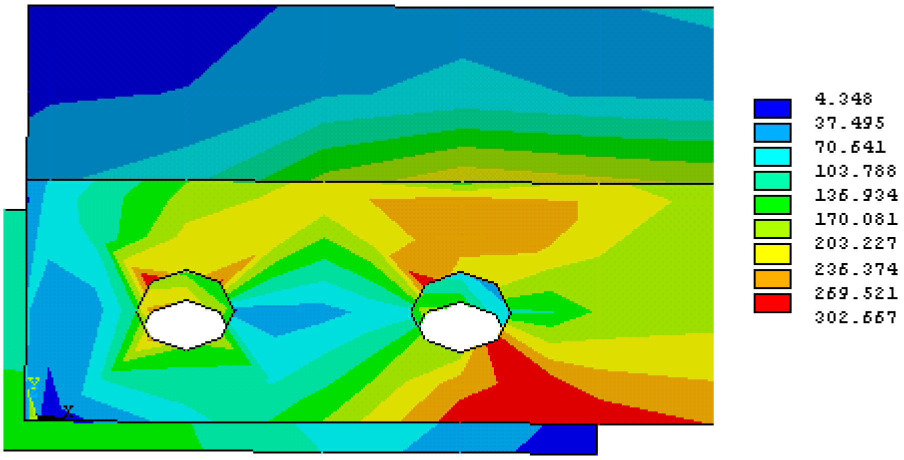

Figure 4c: SVM stresses for two bolts at design loads.

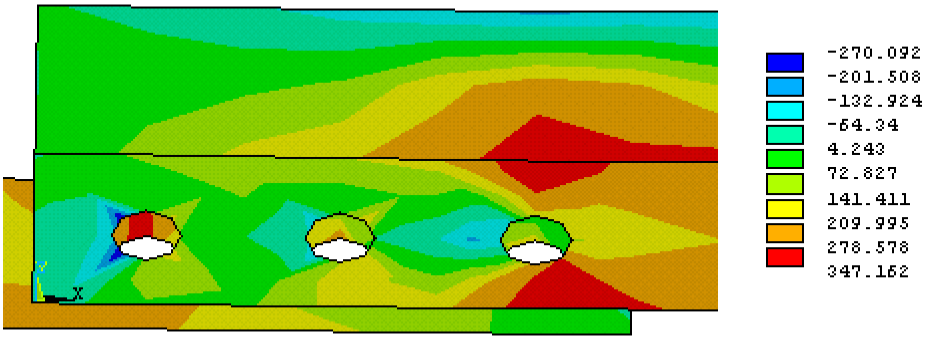

Figure 5a: SX stresses for three bolts at design loads.

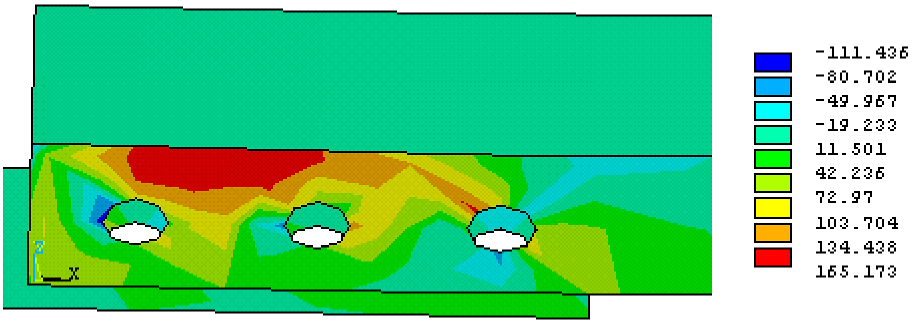

Figure 5b: SXY stresses for three bolts at design loads.

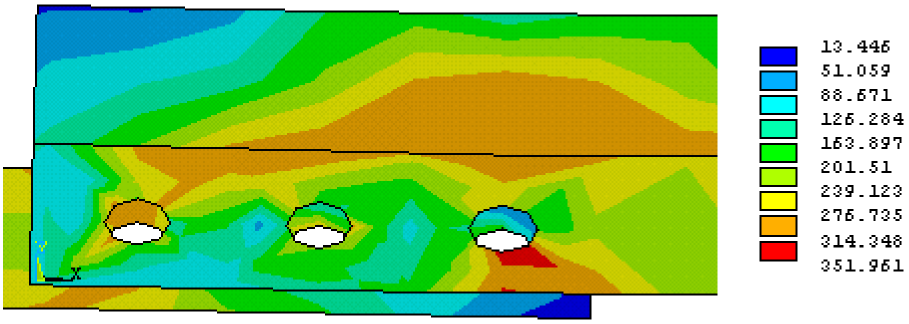

Figure 5c: SVM stresses for three bolts at design loads.

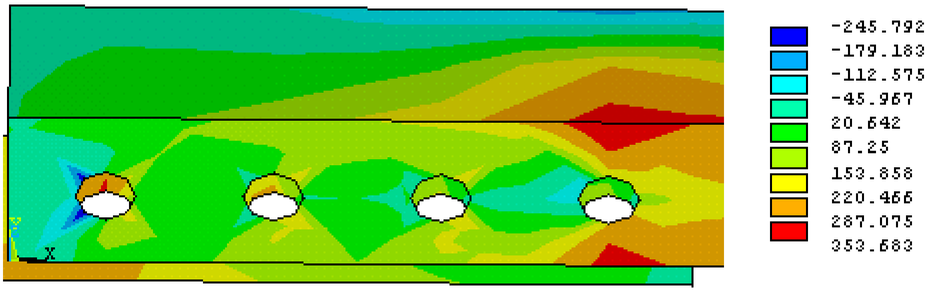

Figure 6a: SX stresses for four bolts at design loads.

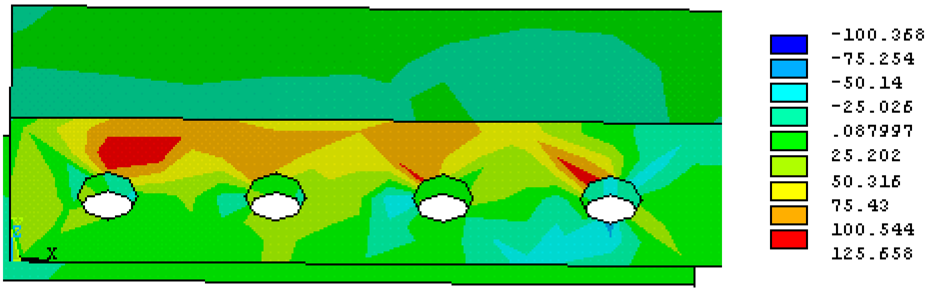

Figure 6b: SXY stresses for four bolts at design loads.

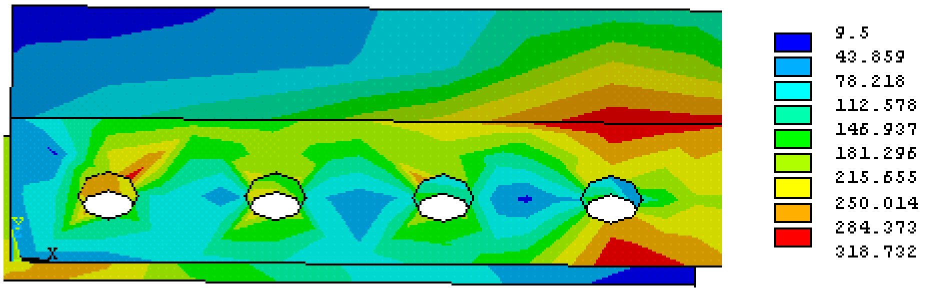

Figure 6c: SVM stresses for four bolts at design loads.

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