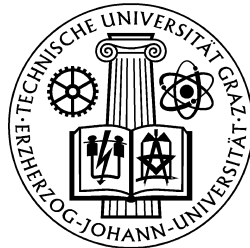


EC 3 - RELATED DESIGN OF SHEAR LOADED CONNECTIONS WITH PLASTIC BEHAVIOUR



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Bolted connections

Fig.1: In the present work the plastic design concept is related to connections subject to eccentric shear loads. On the left side you can see an example of a bolted connection with the components of an eccentric shear load and on the right side there is a welded connection with the resultant of the eccentric shear load.

In the United States the plastic design for these types of connections can be used with handbooks since many years. With the introduction of EC 3 it is possible to use the plastic design concept for connections but EC 3 does not give detailed rules.

Fig.2: Nowadays the most widely used design concept is the linear elastic concept. We assume that the force-deformation relationship of the connection is linear. Connections with a linear elastic behaviour loaded in shear are usually designed by separating the load in 3 components. The horizontal and vertical force components acting in the center of gravity cause a horizontal and a vertical translation. The moment causes a pure rotation about the center of gravity. The single results can be added because of the linear elastic behaviour. The bolt which is mostly stressed is the determining bolt of the connection. Every other bolts are not forced as much as this one.

Fig.3: The realistic behaviour of a connection differs from the linear elastic behaviour. The force-deformation relationship is nonlinear as you can see in principle in figure 3. In this case it is not possible to separate the eccentric shear load in components and add the results for each component as we can do in the elastic behaviour. The whole deformation of the connection is a rotation about an instantaneous center of rotation. The force in a bolt is normal to the line from

the instantaneous center of rotation to the bolt. The deformation of a bolt is proportional to the distance from the instantaneous center of rotation to the bolt. This assumption can be done if the connected sheets are rigid in comparison with the bolts. For example if the distance from the instantaneous center of rotation to bolt 1 is 20 cm and to bolt 2 is 10 cm then the deformation of bolt 2 is one half of the deformation of bolt 1. Although the deformation is one half, the force in the bolt is higher than one half because of the nonlinear force deformation relationship of the bolt.

We assume that the limit load is determined by the maximum deformation of the bolt farthest away from the instantaneous center of rotation. No further force redistribution is assumed.

For the calculation of the limit load it is necessary to know the instantaneous center of rotation. This must be done by a computer program because it is very costly. The procedure is an iteration until equilibrium of the internal forces in the bolts with the eccentric shear load is reached. Simply spoken the algorithm is as follows. You try an instantaneous center of rotation. Then you can calculate the distances from the instantaneous center of rotation to each bolt. The bolt farthest away from the instantaneous center of rotation is the determining bolt. Next you calculate the deformation and the force from the force-deformation relationship for each bolt. The next step is to compare the resultant of the internal forces with the shear load. If they are in equilibrium you got the right instantaneous center of rotation and you can calculate the limit load of the connection. If the forces are not in equilibrium you have to try another instantaneous center of rotation and do the above calculation again. Of course it is necessary to do this search for the instantaneous center systematically with a computer program. Analogous you can calculate the limit load of a welded connection under a shear load if you divide the weld stripes in small pieces. It is also possible to assign a different force-deformation relationship to each bolt or piece of weld.

Fig.4: Here you can see the force-deformation relationship of bolts. The diagram on the left side shows experimental results for different bolt grades and types. The blue curve is for a slip resistant connection with high strength bolts. The others are for bearing type connections with different bolt grades. The maximum deformation of these bolts are approximately 8 mm. This value includes the deformation resulting from slip, bearing, shear and bending of the bolt. The value of the slip including the initial deformation of the hole is approximately 2 mm. The shape of each curve is similar.

On the right diagram you can see analogous curves from formulas. The formula is from the American Institute of Steel Construction (AISC). The axis of the diagram are scaled to unit values. The reference value on the vertical axis is the design shear resistance or design bearing resistance of a bolt. The slip force of the slip resistant bolt is twice as much as of the bearing type bolt. After slip the shape of the curves are the same.

Fig.5: In this diagram you can see the results of a bolted connection with two columns and six rows of bolts. The location of the eccentric shear load is in a distance L from the center of gravity. This eccentricity L divided by the distance of the bolts e is the parameter for the horizontal axis of the diagram. On the vertical axis is the limit shear load related to the design resistance of one bolt. If the shear load is in the center of gravity the design shear load is twelve times the design resistance of one bolt because the connection consists of twelve bolts. If there is an eccentricity the limit load is lower because of the additional moment.

In the diagram you can see three curves. The grey one shows the results of the elastic analysis. The black curve shows the results of the plastic design with a force-deformation relationship according to AISC. Finally the dashed curve is for the results of the plastic design with a force-

deformation relationship including slip. The rise of the design resistance of the connection from the elastic concept to the plastic concept with slip is up to approximately 25 %. The influence of the slip is approximately 5 %.

Fig.6: On the right side the diagram shows the location of the instantaneous center of rotation in relation to the center of gravity for the same connection. The angle from the center of gravity to the instantaneous center of rotation is normal to the direction of the shear load in the linear-elastic concept. In this example the angle is 75 plus 90 is 165 degrees. In the plastic concept the angle differs from the elastic concept up to about 15 degrees in this case.

An analogous situation is given for the distance from the center of gravity to the instantaneous center of rotation. A centric shear load causes only a translation of the connection. So the distance is infinite. On the other hand if there is only a moment then the instantaneous center of rotation is in the center of gravity and the distance is zero.

Tab.1: In this table there are some design resistances of the foregoing connection for different configurations of slip. The rows of the table are for different load eccentricities. The first column show the design resistance from an elastic analysis and the second column from plastic design according to the force deformation relationship of AISC. The rise of the resistance is up to 30 %. The third column show the result if every bolt in the connection has the same slip of 2 mm. The rise of the resistance in comparison to the elastic concept is as mentioned before about 25 %. If there are different values of slip in a bolted connection there can be a positive or negative effect compared to the case with constant values of slip for every bolt. The difference of the design resistance is approximately plus/minus 5 % for this configuration of connection. A positive effect can be received if the determining bolt has a slip value and the others not. A negative effect results if the determining bolt has no slip and the others have some slip.

Fig.7: The next two diagrams show results for a group of four bolts in one column. The left diagram is for a vertical shear load and the right diagram is for a load angle of 45 degrees. The rise of the design resistance of the left connection is lower than for the right case. You can see that the rise of the design resistance depends on several parameters.

Welded connections

Fig.8: Next we will have a look on welded connections. Here you can see experimental results from weld stripes. The curves are for different angles of the direction of the force to the axis of the weld. If the angle is zero then the force acts in the same direction as the axis of the weld. If the angle is 90 degrees then the force is normal to the axis of the weld. The horizontal axis of the diagram shows the deformation in millimetres. You can see that the ultimate deformation for an angle $\zeta=0$ is four times the ultimate deformation as for an angle $\zeta=90$ degrees. On the vertical axis of the diagram the reference value is the design resistance for an angle $\zeta=0$. If the force acts normal to the weld the resistance is approximately 44 % higher than for a force parallel to the axis of the weld. You can see that a small angle of 15 degrees will significantly rise the design resistance of the weld but also that the ultimate deformation is much lower than for an angle $\zeta=0$.

On the right diagram are analogous curves which result from formulas according to Eurocode 3/annex M. Here you can see that the rise of the design resistance is much lower for small angles compared to the curves on the left. The maximum rise is about 22 %. EC3/annex M does not give rules for the ultimate deformation of welds so the same values as from the experimental results are used.

Fig.9: The diagram below show results for a C-shaped weld. The horizontal parameter is the eccentricity of the shear load related to the center of gravity. The reference value for the vertical axis is the design resistance for a centric shear load without a dependence of the angle between the direction of the force and the axis of the weld. The grey curve is the result from an elastic analysis. The dashed grey curve is the result from a simple model according to the figure to the right. Here the eccentric shear load is separated in components. The vertical component is taken from the vertical weld leg. The horizontal component and the moment belongs to the horizontal legs. This model is very conservative for some parameter values. The black curve is the result from the plastic design concept with a force-deformation relationship according to the experimental results and the dashed black curve shows the result for the relationship according to EC3/annex M. In this diagram you can see that there are considerable differences in the design resistance resulting from different design concepts. The resistance varies nearly up to a factor of 2.0 between the elastic and plastic concept according to AISC. The design concept according to EC3/annex M results in a design resistance up to a factor of 1.5 times the elastic values.

Fig.10: This diagram is for a C-shaped welded connection with long horizontal legs. The simple model in this case is very conservative for small eccentricities of the shear load. The difference between the elastic concept and the plastic concept is comparable to the foregoing example. On the right side you can see a square shaped weld. The results are similar.

Fig.11: The effect of the angle between the direction of the force and the axis of the weld can be seen in the next example. Without an eccentricity the elastic and plastic concept results in the same design resistance of the connection. If there is a small eccentricity the plastic design according to AISC will give higher values because of the force-deformation relationship of welds. The plastic design concept according to EC3/annex M does not show this phenomena but the design resistance is considerable higher than the results from the elastic concept.

The last diagram show the result if the shear load acts in an angle of 45 degrees to the axis of the weld. In this case the design resistance for the centric shear load is significantly higher than it was in the example before.

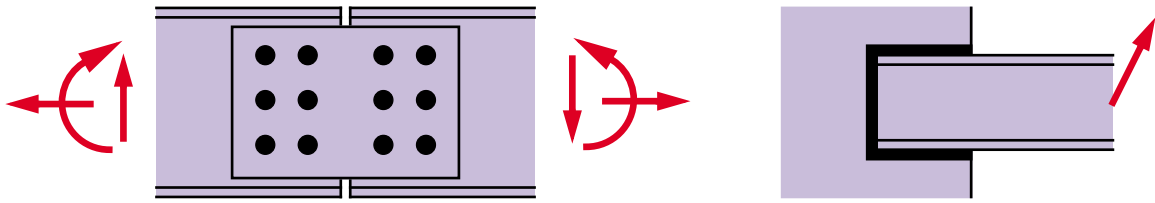


Fig. 1. Connections loaded in shear

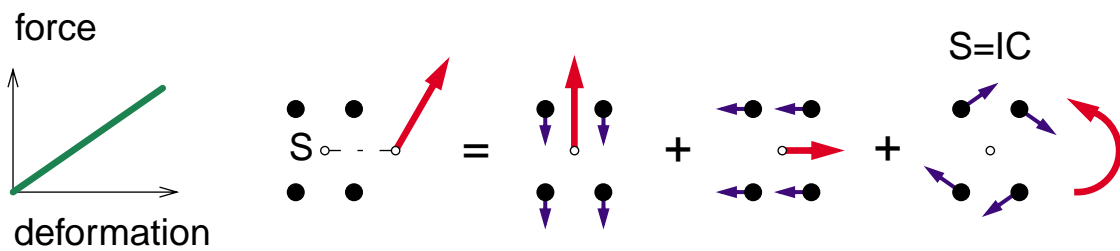


Fig. 2. Linear-elastic behaviour

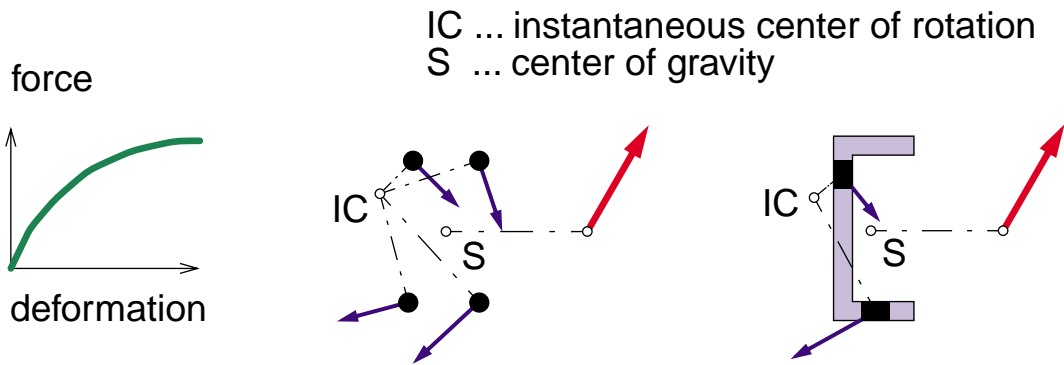


Fig. 3. Plastic behaviour

Bolted connections

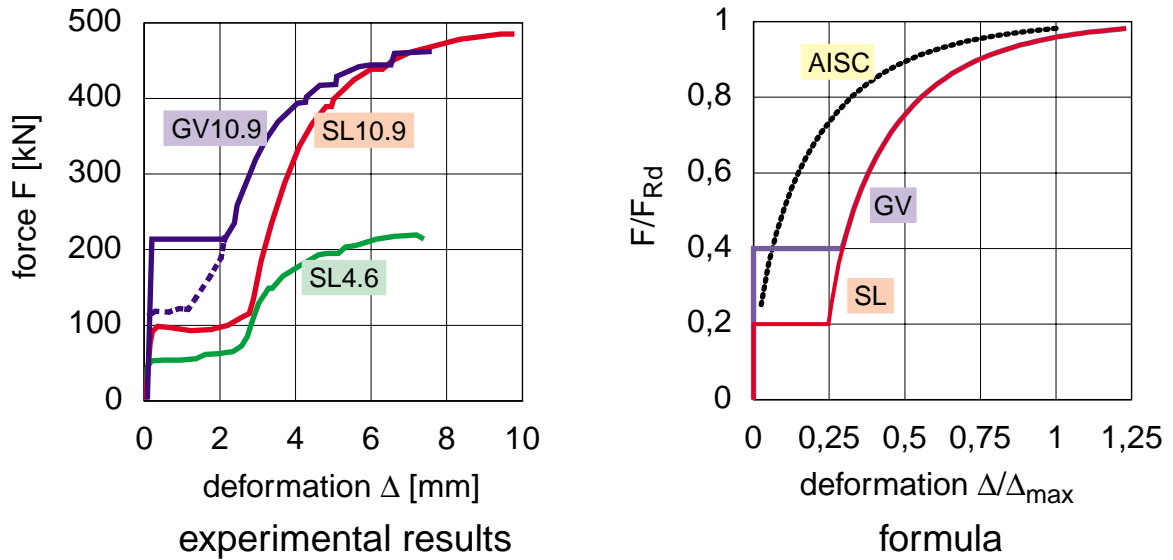


Fig. 4. Force-deformation relationship of bolts

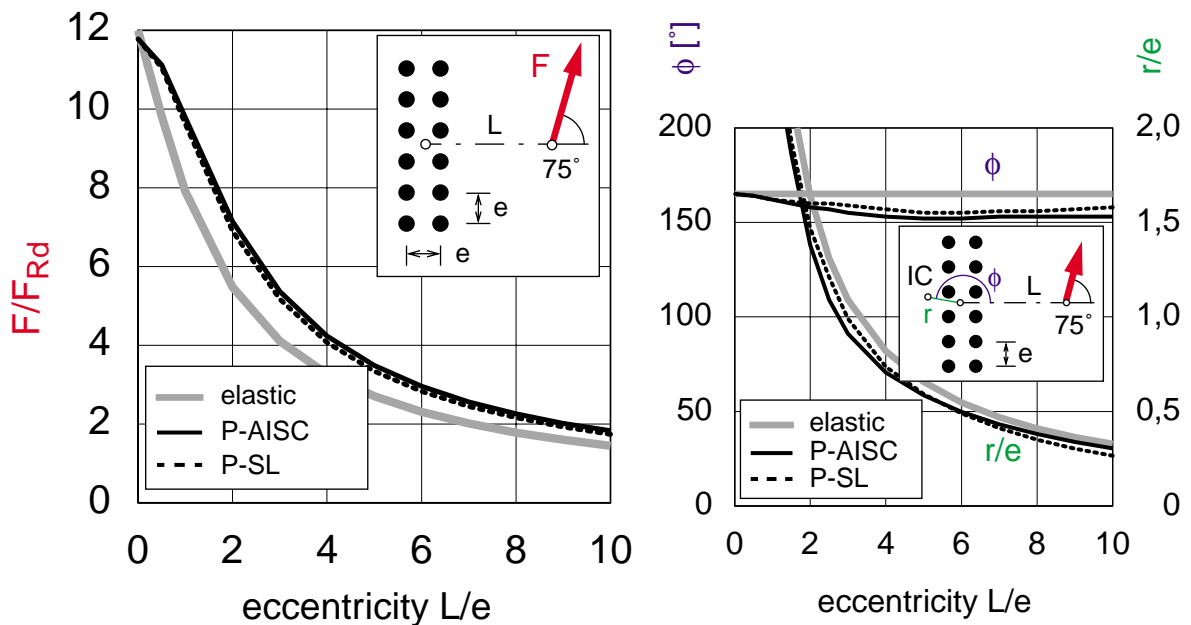


Fig. 5. Design resistance of a bolted connection

Fig. 6. Location of the instantaneous center of rotation

	elastic	P-AISC	P-SL	P-SL	P-SL
0 mm slip ● ○ 2 mm slip					
L/e=2	5.48	7.15	6.90	7.31	6.50
L/e=4	3.27	4.24	4.07	4.33	3.81
L/e=10	1.45	1.83	1.74	1.84	1.63

Tab. 1. Design resistance F/F_{Rd} for different slip

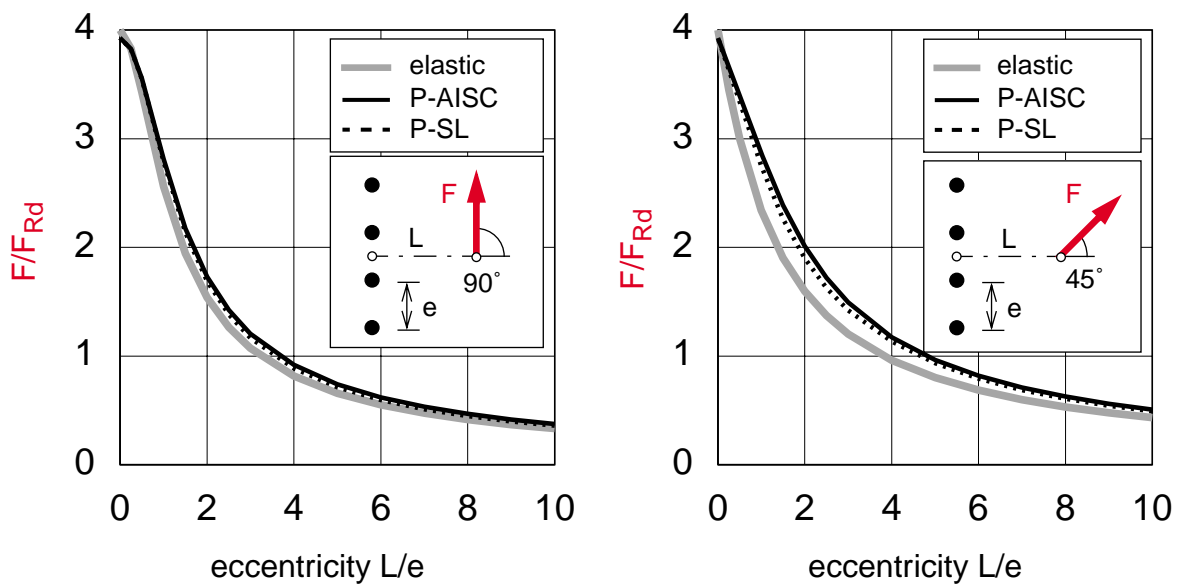


Fig. 7. Design resistance of a bolted connection

Welded connections

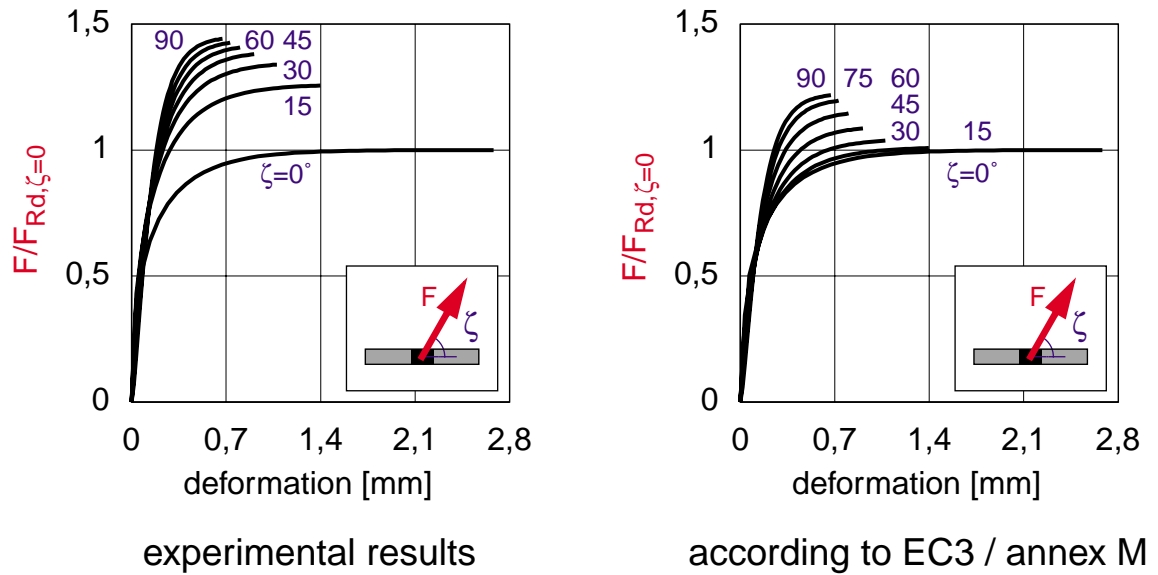


Fig. 8. Force-deformation relationship of fillet welds

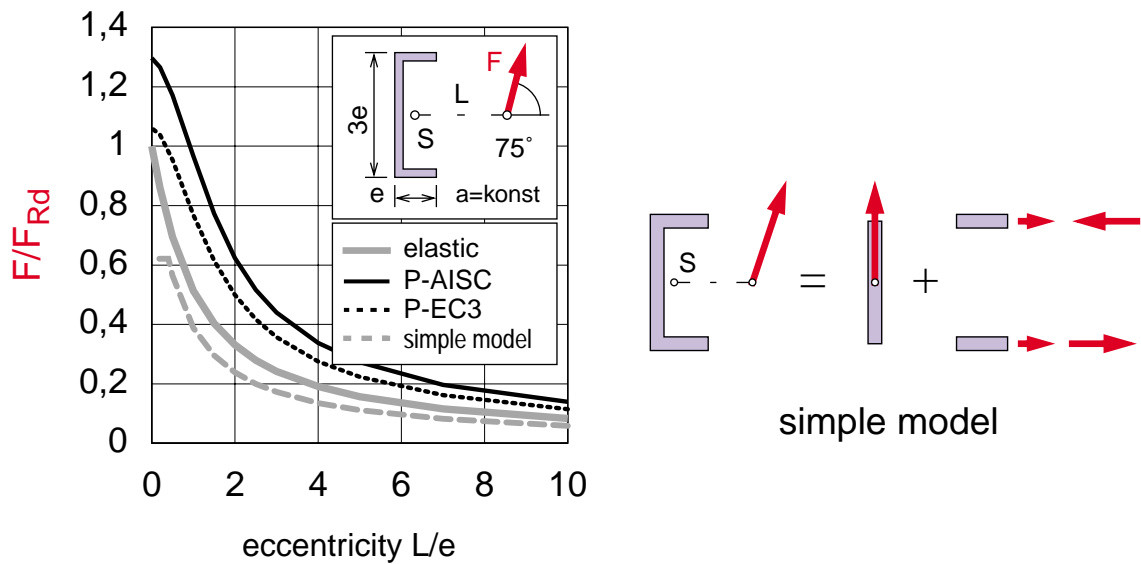


Fig. 9. Design resistance of a C-shaped connection

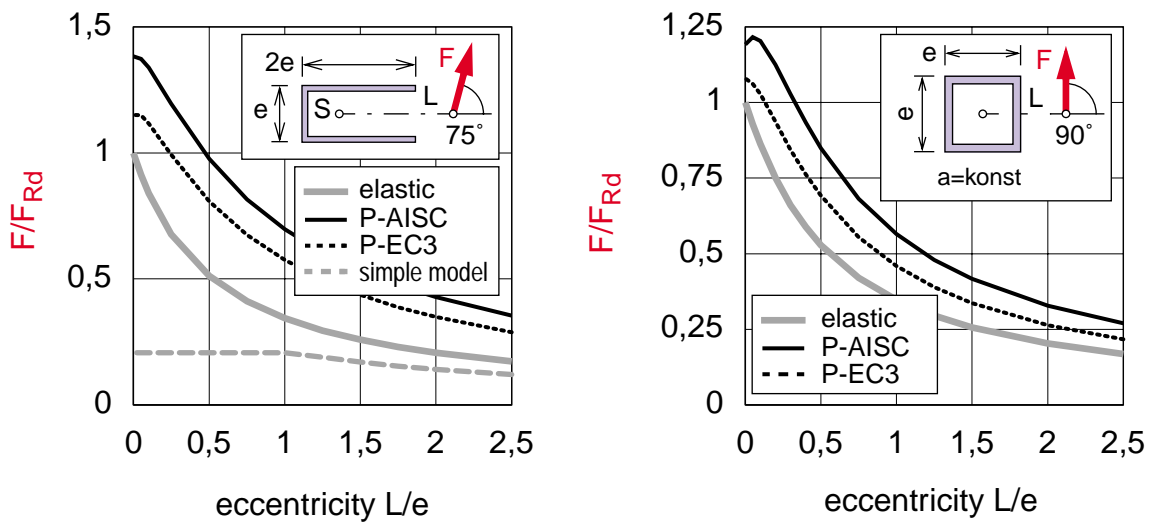


Fig. 10. Design resistance of welded connections

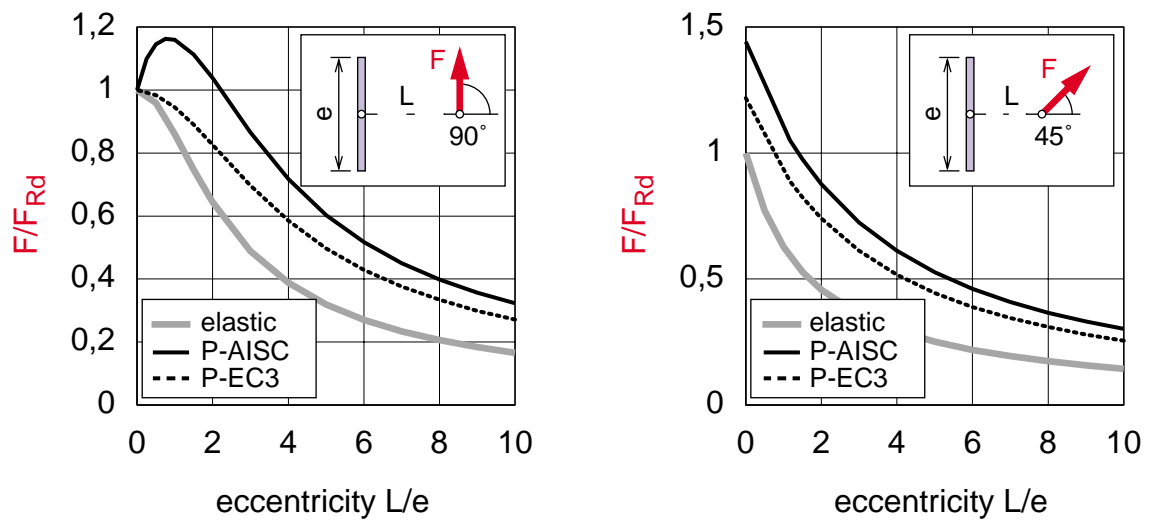


Fig. 11. Design resistance of welded connections

Conclusions

The force-deformation relationship of a bolt or a weld is nonlinear. Therefore the plastic design concept requires the location of the instantaneous center of rotation. The location can be found in an iterative procedure.

The advantage of the plastic design concept is that the design resistance is more realistic and sometimes considerable higher than in the elastic design concept. The safety factor $\gamma_M=1.25$ is relative low. We should think over this factor when using the plastic design concept.

Bolted connections

The resistance of a connection by plastic design is up to 25 % higher than by elastic design. The influence of 2 mm slip reduces the design resistance approximately 5 % compared to a connection without slip. Different slip values in a connection can have a positive or negative effect. The design resistance can be approximately 5 % higher or lower compared to a connection with a constant slip in every bolt.

Welded connections

The resistance of connections by plastic design is up to a factor of 2 higher than by elastic design. The rise depends significantly on the used force-deformation relationship according to AISC or EC 3/annex M. A weld has a considerable dependence due to the angle between the direction of the force and the axis of the weld. Simple models used widely by engineers can be very conservative for inadequate parameter values.