A Component-Based Model for Fin Plate Connections in Fire

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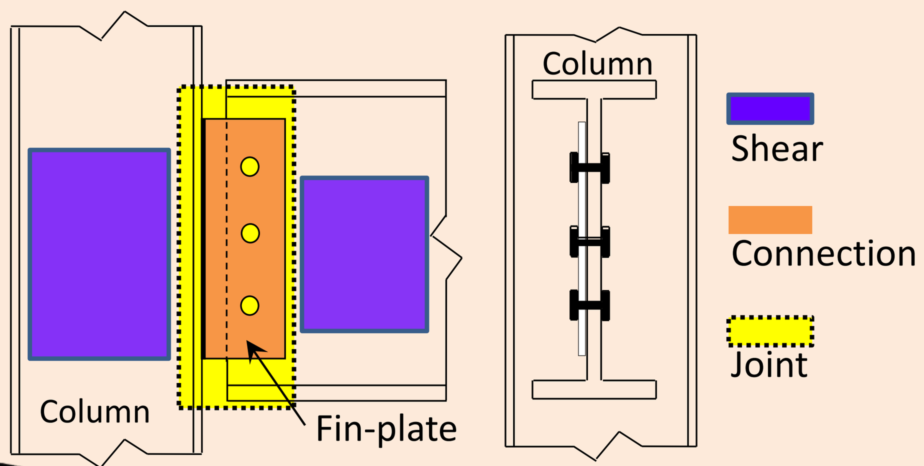
INTRODUCTION

Connections are usually the weakest points in steel and composite structures. In particular, when the floor structure is affected by fire, connections can be subjected to extremely large tying forces in either direction, together with very large rotations. The disproportionate collapse of WTC 7, on 11 September 2001, has now been traced to connection failures arising from these forces. The most practical approach to integrating the behaviour – and failure - of connections into whole-structure modelling used in performance-based design of steel structure is the component-based method. In this research, the behaviour of fin-plate connections at elevated temperatures is being investigated with a view to integrating their characteristics into the finite element analysis software VULCAN .

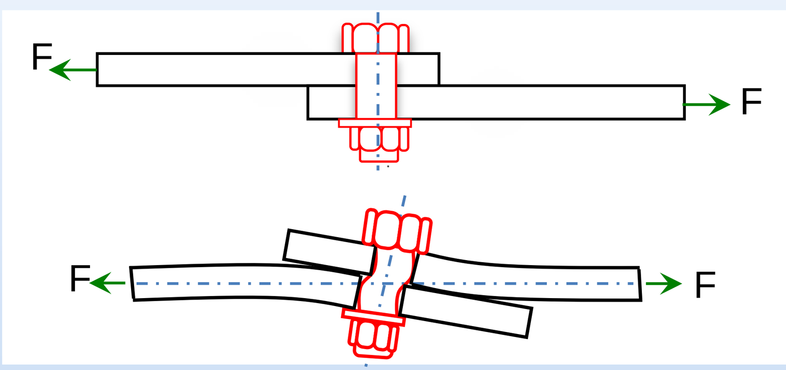
Fin-plate connections, which come into the category of shear connections, consist of a single plate welded to the column, and attached to the beam using two or more bolts through its web. This simple connection is intended primarily to transfer vertical shear, and is assumed not to transmit significant moment from the beam to the column.



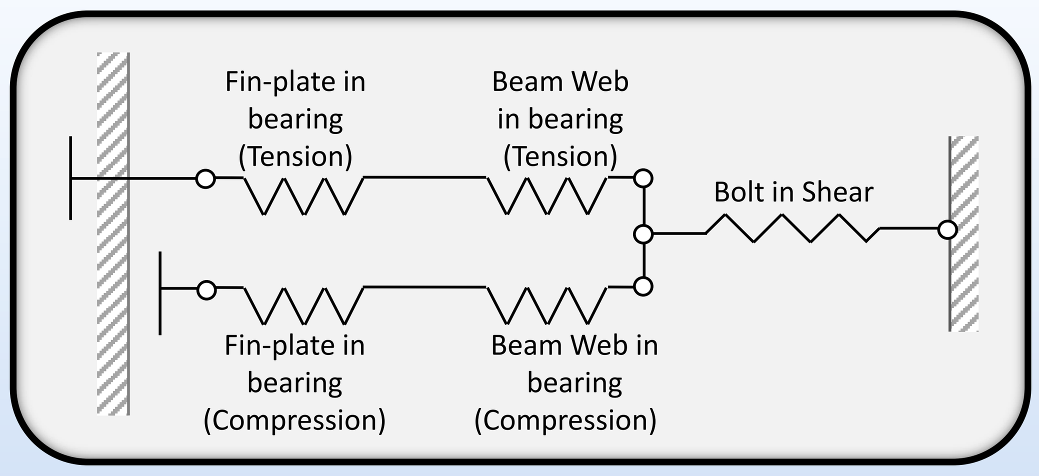
FIN-PLATE COMPONENT MODEL

A mechanical model is formed based on identification of individual components, following the load path through this kind of joint. The model divides the joint into zones of fundamental behaviour which are called components. The lap joint component model consists of three fundamental Components (“springs”) in series: (i) Fin-plate in bearing, (ii) Bolt in shear, (iii) Beam web in bearing.

A shear connection can be represented by extending the behaviour of a single-bolted lap connection. This is a combination of two plates (fin-plate and beam web) with a bolt fastening them through an over-sized bolthole.

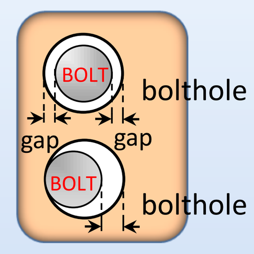


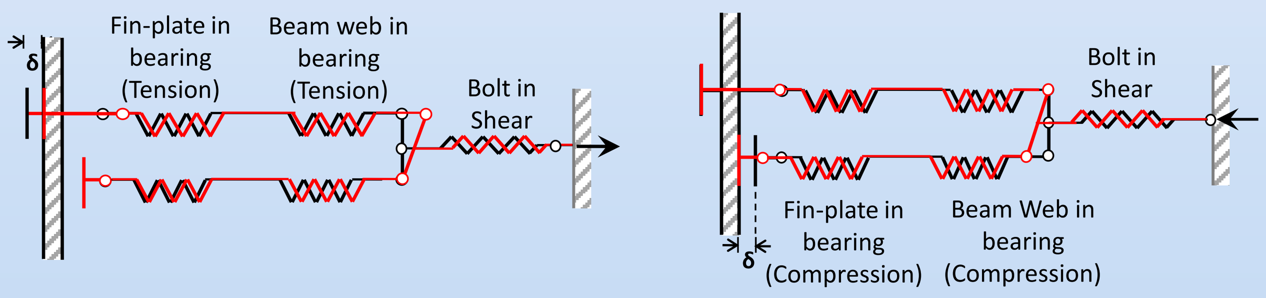
Typical single-bolt lap-joint
(a) undeformed (b) deformed



Each individual component is assumed to perform independently, as expressed by its own force-deflection characteristic curves. The influence of elevated temperature is accounted for by degradation of its stiffness and strength properties.

The component model has been modified particularly to account for the effect of the over-sized bolthole in fire. When loaded, the component model will be activated once the gap closes (the bolt touches the bolthole). Similar action is assumed during both compressive and tensile loading.





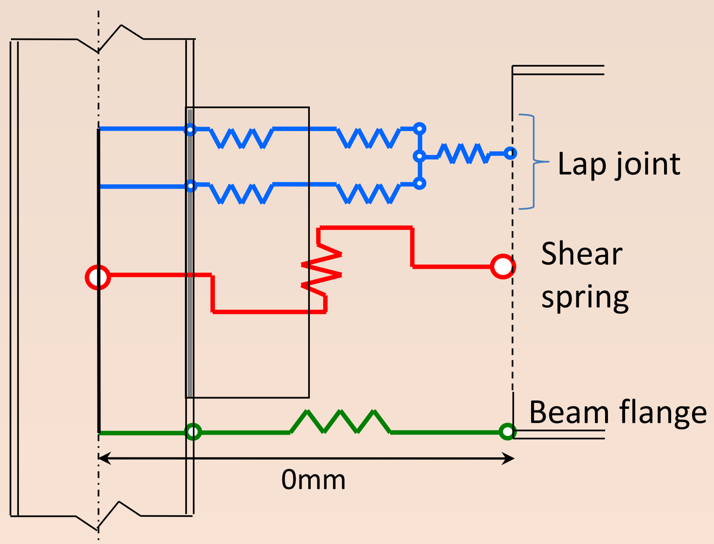
Component-based bolt row model subjected to (a) tension (b) compression.

COMPONENT CHARACTERISTIC

- The joint element is modelled as an assembly of component springs and rigid links, with no physical length.
- An additional vertical shear spring, presently assumed to be rigid, is included to transfer the vertical shear force from one node to the other.
- A component spring at the location of lower beam flange is adopted to account for contact made by the lower flange of the beam and the column face, at high rotation.

The component method is used to formulate a component-based finite element which can be incorporated in VULCAN. The non-linear behaviour of each individual connection component is solved iteratively.

$$\Delta F = K_c'\Delta u$$



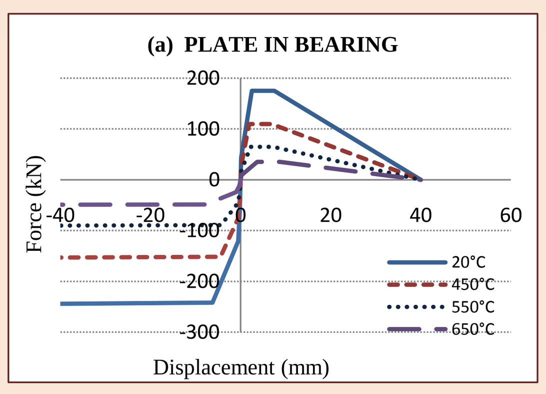
Layout of connection element

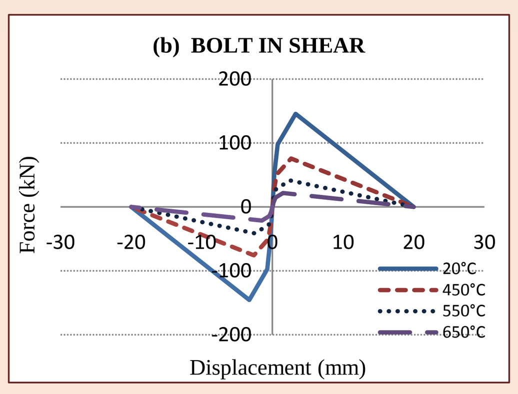
The active components which contribute to the deformations, or limit the strength of the joint are bearing and bolt shear failure . The ductility required in a fin-plate connection is provided by the plate yielding, and by bearing deformation of the bolt holes. The design procedure classifies the failure modes into ‘ductile’ and ‘brittle’, and attempts to ensure that the ductile failure modes will take precedence over the brittle ones.

The strength of the plate bearing component is highly affected by the lateral confinement of the material surrounding the loaded hole. When the bolt is close to the end of the plate, the edge distance of the plate controls the tear-out failure.

For the bolt-in-shear component, it is assumed here that the shear resistance decreases to zero at a displacement equal to the bolt diameter. The ‘down-hill’ part of the force-displacement curve is defined on the basis of the calculation of the residual connected area of the bolt

Plate bearing



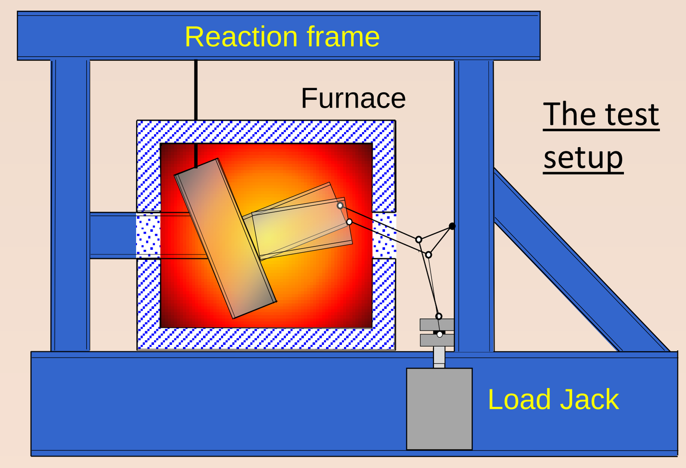


Bolt shearing

EXPERIMENTAL VALIDATION OF COMPONENT MODEL

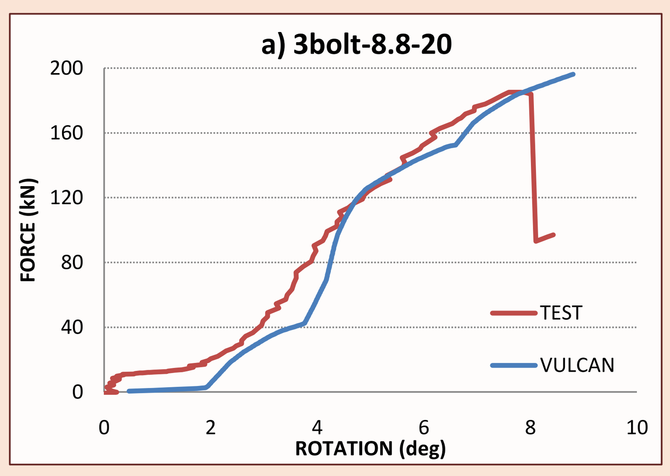
The Sheffield group has conducted fire tests to investigate the capacity and ductility of flush endplates, flexible endplates, fin-plates and web cleats, under combinations of tying force, shear and rotation.

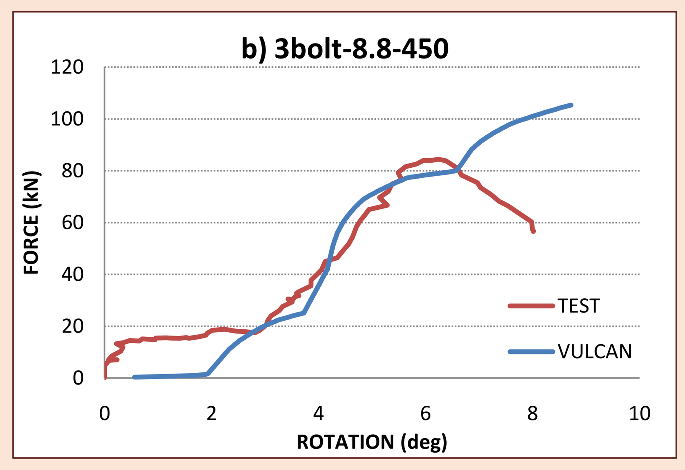
The electric furnace has 1.0m^3 internal volume with strain gauges and digital cameras to measure the forces and deformations of the specimen, To allow free movement of the furnace bar, the column was tilted by 25˚ in the furnace.

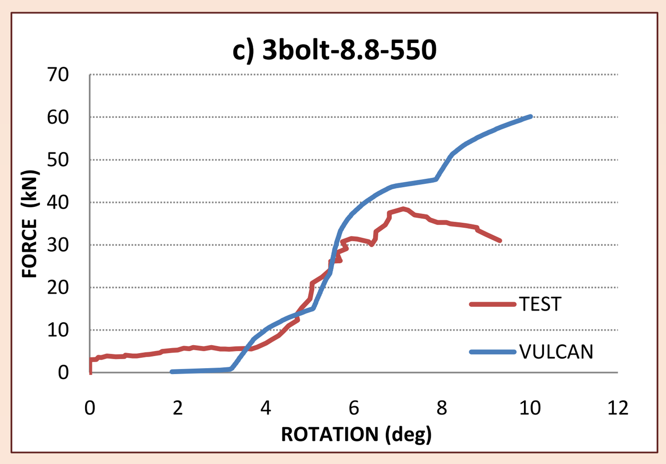


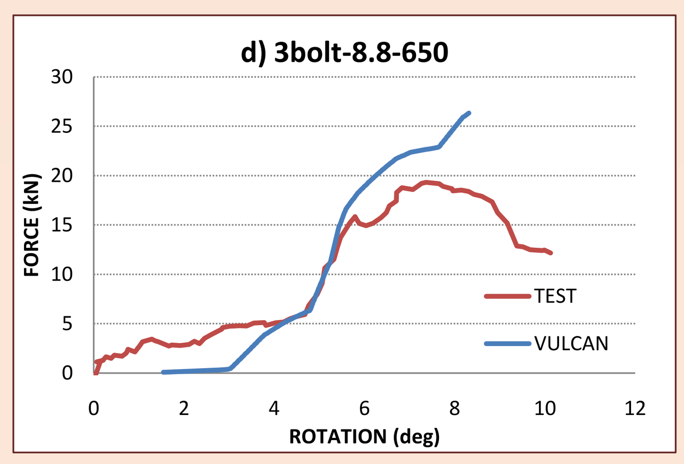
The test setup

The responses of the component model during the loading phase agree well with the test results, up to the point at which the lower beam flange spring was activated. When the model is loaded, the geometry changes, causing a discontinuous relationship between the forces and rotational displacements. Subsequently, the second-order geometric effects are taken into account in the VULCAN analysis, which creates increased internal moments caused by additional bending of the cantilever member. At elevated temperatures, the predicted maximum resistance is higher than was observed in the tests. This is to be expected, as it is mainly caused by successive failures of the bolts beyond their maximum nominal resistance.









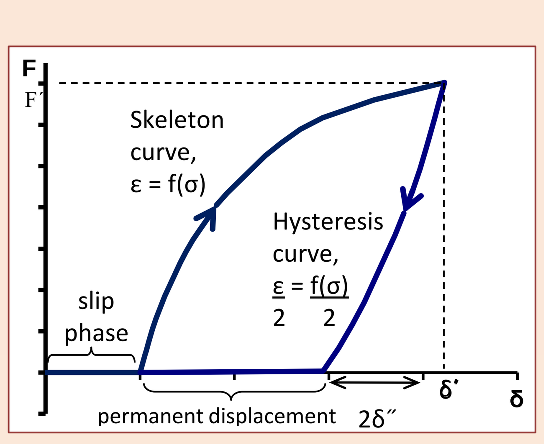
Force-rotation comparisons for inclined tying forces at temperature a)20°C b) 450°C c) 550°C d) 650°C

CURRENT & FUTURE WORK

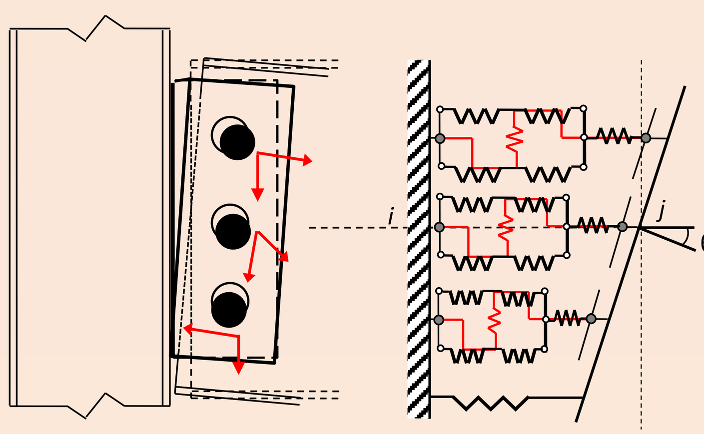
The newly developed component model has now been incorporated into VULCAN. A more comprehensive understanding of the joint behaviour can be achieved by carrying out further work:

- **Unloading of the connection model using the classic Massing Rule to consider cyclic behaviour at elevated temperatures.** A modification to Massing’s rule is applied to take account of the initial slip phase, which only allows force transition into the opposite quadrant when contact is re-established.
- **Application of connection element in sub-frame modelling as a parametric study.**
- **Influence of combined forces (horizontal and vertical forces)** . Complexities in modelling the fin-plate connection arise from the combined action of horizontal and vertical bolt forces.

The vertical action, which is currently represented by a single shear spring for all bolt rows, may not be the best representation of the connection’s response in fire. A refined model, which incorporates a vertical spring in each bolt row, is an initial attempt to investigate the possible effect of combined loading at each row.



Massing Rule for fin-plate connection



Combined forces at bolt rows

CONCLUSION

At elevated temperature, failure of fin-plates is dominated by bolt shear failure, but significant bearing deformations to the bolt holes may be caused before the bolts shear.

On the basis of numerical modelling, the force-deflection-temperature component models for the fin-plate components have been derived, and have been embedded in VULCAN. This is intended to enable comprehensive analysis of whole structures or large substructures, up to failure, including the interaction between members, via realistic connection behaviour.