A COMPONENT-BASED MODEL FOR FIN-PLATE CONNECTIONS IN FIRE

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INTRODUCTION

Connections can be classified according to their rotational stiffnesses, which are classed as rigid, simple or semi-rigid. Semi-rigid assumptions can be considered to assess the stiffness and capacity of steel framing systems most accurately. The benefits of this treatment are extensively documented, and there is a general acceptance that semi-rigid design results in efficiency, lightness and economical ambient-temperature design. In fire conditions, due to the combinations of thermal expansion and material weakening, beams can be subjected to high normal forces, both in compression (at fairly low temperatures) and tension (at high temperatures), in addition to extremely high rotations, if their ends are fixed horizontally. These beam forces have to be sustained by the connections unless some movement of the beam ends, which relieves the forces, is permitted. Such movements can occur because the connected members move, or because the connections themselves have enough ductility to reduce the forces transmitted. In any case, the vertical shear forces, which the connections are designed to sustain at ambient temperature, are generally largely unaffected by the effects of fire.

Incorporating semi-rigid connections into global thermo-structural analysis requires tools and methods to facilitate the analytical design process, as joint characteristics can clearly have a significant influence on the survival time of the structural assembly during a fire. Advanced finite element models of connections involve high preparation time and computational cost, hence limiting their use for practical design purposes, despite being capable of highly reliable nonlinear joint simulation. Due to the inadequacy of structural databases, full-scale or isolated fire testing is inevitably required to provide the most accurate representation of connection response, although this is unlikely to be an economically appealing solution.

An intermediate approach to incorporating connection behaviour, known as the component-based modelling approach, has now been widely developed for ambient-temperature design. Eurocode 3 has implemented this approach to model the strengths and initial stiffnesses of steel joints for semi-rigid design. This approach constructs a connection from extensional zero-length “spring” elements and rigid links, representing the characteristics of its main structural zones realistically. Each active component makes its contribution independently, through its structural properties. This simplified method allows connections and structural system configurations to be varied rapidly, and thus the impact of various parameters on the system’s global performance can be analysed.

1 IDENTIFICATION OF ACTIVE COMPONENTS

A very widely used simple connection is the fin-plate connection, classed as a shear connection, which consists of a pre-drilled single plate, welded to the supporting column flange or web, and bolted to the beam web at a number of single- or double-bolted rows (Fig.1a). Simple connections are assumed to develop a moment at the beam end less than or equal to 20% of the fixed-end moment, while the end rotation is greater than or equal to 80% of the end rotation in a simply-supported beam. They are invariably cheaper to fabricate than moment-resisting connections as fabrication is simple, and fin-plates can be standardised. Cost advantages largely influence the choice of this connection, and erection on site is simple. As a simple shear connection, normal design concerns only the strength and ductility needed to transfer the vertical beam end reaction to its support. In fire conditions the connection also needs to provide sufficient rotational ductility to accommodate the rotation of the beam end, as well as a reasonable amount of horizontal movement.
Failure of fin-plate connections at high temperatures involves response to a combination of beam end shear and normal forces, and large rotations. In order to understand the load transfer via bolt shearing, it is convenient to represent a simple shear connection by a lap joint (Fig. 1b).

![Diagram showing fin-plate connection, lap joint, plate bearing, and bolt in shear.]

Fig. 1: (a) Fin-plate connection; (b) lap joint; (c) plate bearing; (d) bolt in shear.

1.1 Plate in bearing

Bearing failure of the plates is strongly affected by the lateral constraint to the contact zone by the surrounding material in its vicinity. Yielding of the plates does not cause a substantial loss of load capacity (Fig.1c), and is therefore generally treated as a ductile failure mode. The desired failure mode of a shear connection, as implied by the design guides, adopts the conservative design recommendation that plate bearing is the resistance which should govern design. When the bolt is close to the end of the plate, its edge distance controls the tear-out and bearing (which are treated as a single limit state). However, moving away from the end of the plate results in large bearing deformation of the bolt hole without occurrence of tear-out failure. A typical force-displacement relationship with respect to temperature is shown in Fig.2a.

Rex and Easterling concluded that the initial stiffness associated with a plate in bearing depends on three primary stiffness values (bending ($K_b$), shearing ($K_v$), and bearing ($K_{br}$)) based on detailed investigation of a single-bolt lap plate connection. Sarraj distinguishes two cases of bearing from a finite element parametric study in order to determine the plate bearing resistance using the most effective curve-fit values; these involve bolts with a small end distance ($e_2 / d_b < 2$) and with a large end distance ($e_2 / d_b > 2$). The key difference between these studies was the degree of tightening of the nut on the outer surfaces of the plates. Rex and Easterling’s equations are:

\[
K_{br} = \Omega t F_z \left( \frac{d_d}{25.4} \right)^{0.8}
\]

\[
K_b = 32 Et \left( \frac{e_2}{d_b} - 0.5 \right)^3
\]

\[
K_v = 6.67 G t \left( \frac{e_2}{d_b} - 0.5 \right)
\]

\[
K_i = \frac{1}{K_{br}} + \frac{1}{K_b} + \frac{1}{K_v}
\]

Where $e_2$ is the end plate distance (mm), $d_b$ is the diameter of the bolt (mm), $\Omega$ is a temperature-dependent parameter for curve fitting.

1.2 Bolt in shear

The bolt shear failure mode may significantly affect the integrity of the structural system because it has inadequate ductility to ensure simultaneous plastic distribution of the forces carried by the bolts, and may therefore allow progressive failure. The relationship between the bolt shear deformation...
and the force is given in Eq. (5) by a modified Ramberg-Osgood expression for relative bolt deflection:

$$\Delta = \frac{F}{K_{v,b}} + \Omega \left( \frac{F}{F_{v,rd}} \right)^n$$

(5)

Where $F$ is the level of shear force [N], $K_{v,b}$ is the temperature-dependent bolt shearing stiffness [N/mm], $F_{v,rd}$ is the temperature-dependent bolt shearing strength [N].

In the study by Sarraj, bolt shearing failure was assumed to occur immediately after the maximum shear resistance, $F_{v,rd}$ was reached. However, a gradual decrease of shear resistance was observed during tests carried out by Yu at elevated temperatures. It is therefore assumed here that the shear resistance decreases to zero at a displacement equal to the bolt diameter. Example characteristic curves with respect to temperature of a bolt in shear are shown in Fig. 2b.

![Figure 2: Properties of components: (a) Plate in bearing; (b) Bolt in shear.](image)

2 JOINT MODELLING

Previously, component-based models of fin-plate connections have been developed by Sarraj and Yu based on two-noded spring elements. The lap-joint zone consists of three fundamental components with no physical length, placed in series, for each bolt row: fin-plate in bearing; bolt in shearing; beam web in bearing. These component models include a friction spring in parallel with this basic spring series. The simplified friction load-deflection characteristic, however, generates low slip resistance, and has little influence on the connection’s behaviour.

![Figure 3: (a) Component-based model of a bolt row of a fin-plate connection (b) Component-based model subjected to tension and compression](image)

A component-based model of a single-bolt-row of a fin-plate connection with no physical length is illustrated in Fig. 3a. The minimal effect of the frictional resistance between the two plates has been neglected here. The picture of the component-based model of a whole two-row fin-plate connection shown in Fig. 3b demonstrates that, during a complete analysis, tension and compression do not
follow the same lines of action. The load capacity is predominantly determined by the assembly of springs, from which the weakest individual component spring initiates failure.

2.1 Component-based model in VULCAN

The joint element is modelled as an assembly of component springs and rigid links, concentrating on the beam-to-column connection zone. An additional component spring at the lower beam flange level is adopted to account for contact between the lower flange of the beam and the column face at high rotation. A highly simplified version of the model consists of two horizontal rows; a single lap joint, the beam flange/column face contact, and a vertical shear spring, as shown in Fig. 4.

![Diagram of Forces and Displacements](image)

**Fig. 4:** Forces and displacements of a simplified connection element.

Each degree of freedom of the assembled springs is displaced individually to derive the stiffness matrix of the connection element, which eventually has three degrees of freedom (two translational \( u, w \) and one rotational \( \theta \)) at each node. By solving for the global force and moment equilibrium of the whole element, the force-displacement relationships of the degrees of freedom can be calculated. The final tangent stiffnesses of the connection element are shown below.

\[
K'_{11} = \sum_{i=1}^{n} k'_{\text{lap},i} + k'_{\text{beamflange},i}
\]

(6)

\[
K'_{15} = K'_{25} = \sum_{i=1}^{n} k'_{\text{lap},i}l_{\text{lap},i} + k'_{\text{beamflange},i}l_{\text{beamflange},i}
\]

(7)

\[
K'_{11} = k'_s
\]

(8)

\[
K'_{15} = K'_{25} = \sum_{i=1}^{n} k'_{\text{lap},i}l_{\text{lap},i} + k'_{\text{beamflange},i}l_{\text{beamflange},i}
\]

(9)

In these equations, \( n \) is the number of component bolt rows, and the indices “lap” and “beamflange” indicate the lap joint assembly and beam flange spring respectively. The index \( s \) indicates the shear spring. Due to the simplicity of this mechanical model, the tangent stiffnesses can be incorporated in VULCAN using its existing spring element infrastructure. The component model subroutine subsequently provides the necessary incremental displacement vector for the connection element, and returns the tangent stiffness matrix and force vector to the main routines.

2.2 Loading and unloading of component model

The classic Massing rule\(^8\) is incorporated so that each individual component will respond realistically to load reversals. The hysteresis curve in unloading (Fig. 5a) from the point at which strain reversal occurs, is the loading curve, scaled by a factor of two and rotated 180°. A modification to the Massing rule is applied to account for the initial bolt-slip phase, and only allows force transition into the opposite quadrant when contact is re-established, as shown in Fig. 5b. During the heating phase, the softening of the material is defined by force-deflection characteristics which are functions of temperature. The permanent plastic deformation, which is recalculated after each temperature change, is considered as unaffected if the temperature changes. Thus, each force-
displacement curve at different temperatures necessarily has to unload completely through the same point. The unloading curve for a new temperature intersects with the previous unloading path at the zero-force axis, and this point is used as the reference point, $\delta_{p,TI}$.

![Diagram](image)

Fig. 5 Massing Rule for fin-plate connection at varying temperature.

3 EXPERIMENTAL VALIDATION AT ELEVATED TEMPERATURE

Yu et al.$^7$ carried out an experimental investigation of the robustness of steel connections at elevated temperatures for flush endplates, flexible endplates, fin-plates and web cleats. The design setup for fin-plates used 200mm deep × 8mm thick fin-plates with three rows of bolts, designed in accordance with UK design recommendations.$^7$ Inclined tying forces were applied to represent the catenary action phase of a beam in fire. The results shown in Fig. 6 are for applied force inclinations of $\alpha=35^\circ$ at ambient temperature and at 450°C, to represent a temperature range in which the properties of both structural and bolt steels have started to degrade rapidly.

![Graphs](image)

Fig. 6: Comparisons of test results to the component model (load angle 35°) at steady-state temperatures; (a) ambient temperature, (b) elevated temperature.

The responses of the component model and the test results are generally in close agreement for similar loading arrangements. Comparisons of the force-rotation relationship assume M20 bolts, initially installed centrally in clearance holes of 22mm diameter, producing 2mm initial slip between the plates. This initial slip ends with the first positive contact of the bolt against the bolt hole, which considerably influences the rotational response, as shown in Fig.6a. As the model is loaded, geometry changes cause the relationship between the force and rotational displacement to be non-linear. Subsequently, the second-order geometric effects, which create increased moments, are taken into account in the finite element analysis.

The resistance gradually increases after positive contact has been made by the bolt with the plate, until the maximum resistance of the top bolt is exceeded. The bottom flange subsequently comes into contact with the column face, resulting in a stiffer deformation response. The connection
strength is then controlled by consecutive bolt failures until the lowest bolt reaches its ultimate load. The component model was able to produce relatively close predictions of the maximum resistance and the rotational ductility of a connection, at both ambient and elevated temperatures.

4 CONCLUSION

A component-based connection model allows the behaviour of connections to be included in practical global thermo-structural analysis, provided that knowledge about the characteristics of key components is available from test data, numerical simulations or analytical models. At this stage, a basic component model for fin-plate connections has been developed and successfully incorporated in VULCAN. The stiffness matrix of the model has been derived to generate the connection’s response to combinations of forces and displacements, and has subsequently been validated both at ambient and elevated temperatures. This component model, when embedded in VULCAN, allows direct analysis of whole structures or large substructures, including consideration of the interaction between realistic connection behaviour and that of the adjacent structural members.

A major modification to the model, which helps it to consider the real situation in fire, allows the lower beam flange to come into contact with the column face when the connection has undergone large rotation. It has been found that the complex nature of load reversal during a fire can be represented by adapting the Missing Rule, but with modification of the initial slip phase to account for the usual case where bolt holes are larger than the bolts. As part of the global structural assembly of beam-column, slab and connection elements, the component-based model will guarantee that the connection deformations are accounted for within the equilibrium of the whole assembly. This can be beneficial not only in design but also in assisting in the interpretation of experimental and analytical responses of connections within structures in fire.

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