The Development of a Component-Based Connection Element for Endplate Connections in Fire

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Cardington Beam-Column Joint after Fire
Test # 7

Endplate fracture
Beam flange buckling

Introduction
Why and How to Predict?

• For safety and overall stability of the structure, the connections must stay connected, even when beams are highly distorted.

• In performance based design, this is the responsibility of the engineer!

Introduction

Connection behaviour with Component Method

3D frame analysis with VULCAN

Finite Connection element

Safe and economic fire design
The Component Method

- Separating the zones of fundamental behaviour ("components") within a joint.
- Predicting the Force-Displacement behaviours.
- Reassembling a model of the joint with springs.

Introduction
The FEM Software Vulcan

- Non-linear 3D finite element software for structures in fire
- Developed at the University of Sheffield over the last 15 years

www.vulcan-solutions.com
• Beam-end and centre line of column assumed to remain plane
• Tension and compression forces have different lines of action
• Only depends on the geometry and the material of the connection
Basic Form of the Connection Element

Spring models of the Component Method must be translated into non-linear FEM.

\[ \Delta F = K'_c \Delta u' \]

Incremental force vector
Incremental displacement vector
Tangent stiffness matrix

2D spring model used for derivation of stiffness matrix
Derivation of the Stiffness Matrix

Principle of virtual displacements used to find the stiffness of each degree of freedom

\[
\begin{align*}
\delta_{1,i} & \quad F_1 = k_1 \delta_{1,i} \\
\delta_{3,i} & \quad F_3 = k_3 \delta_{3,i}
\end{align*}
\]

\[
\begin{align*}
\beta_i = 1 & \quad w_i = 1 \\
\phi_i = 1 & \quad \delta_{3,i} \\
\end{align*}
\]

\[
\begin{bmatrix}
N_i \\
V_i \\
M_i
\end{bmatrix}
= \begin{bmatrix}
(k_1 + k_3) & 0 & (l_1 k_1 - l_3 k_3) \\
0 & k_2 & 0 \\
(l_1 k_1 - l_3 k_3) & 0 & (l_1^2 k_1 + l_3^2 k_3) \\
\end{bmatrix}
\begin{bmatrix}
\delta_{1,i} \\
\delta_{3,i} \\
\phi_i
\end{bmatrix}
= \begin{bmatrix}
-k_1 - k_3 & 0 & -(l_1 k_1 - l_3 k_3) \\
0 & -k_2 & 0 \\
-(l_1 k_1 - l_3 k_3) & 0 & -(l_1^2 k_1 + l_3^2 k_3) \\
\end{bmatrix}
\begin{bmatrix}
\delta_{1,i} \\
\delta_{3,i} \\
\phi_i
\end{bmatrix}
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\end{bmatrix}
\begin{bmatrix}
u_i \\
w_i \\
\phi_i
\end{bmatrix}
\]

Implementation

N

Buro Happold
Generalisation of the Stiffness Matrix

Full 3D tangent stiffness matrix of the connection element

\[
K'_c = \begin{pmatrix}
K'_{11} & 0 & 0 & 0 & K'_{15} & 0 \\
0 & 0 & K'_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
K'_{51} & 0 & 0 & 0 & K'_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-\infty & 0 & 0 & 0 & 0 & -\infty \\
\end{pmatrix}
\]

\[
\begin{pmatrix}
-K'_{11} & 0 & 0 & 0 & -K'_{15} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-K'_{51} & 0 & 0 & 0 & -K'_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-\infty & 0 & 0 & 0 & 0 & -\infty \\
\end{pmatrix}
\]

with

\[
K'_{11} = \sum_{i=1}^{n} k'_{T,i} + \sum_{i=1}^{2} k'_{C,i} \\
K'_{33} = k'_s \\
K'_{55} = \sum_{i=1}^{n} l^2_{T,i} k'_{T,i} + \sum_{i=1}^{2} l^2_{C,i} k'_{C,i} \\
K'_{15} = K'_{51} = \sum_{i=1}^{n} l_{T,i} k'_{T,i} + \sum_{i=1}^{2} l_{C,i} k'_{C,i}
\]

and \( n = \) number of bolt rows.
Relocation of the reference axis

In Vulcan, the beam and the slab elements share the same nodes and are separated by an offset. The same technique has been used for the connection element.

The offset is added to the lever arms of the springs.
Component Models used: Tension zone

The simplified elevated temperature F-δ models by Spyrou have been used for endplate and column flange.

Failure Mode 1
Failure Mode 2
Failure Mode 3

An equivalent spring is calculated from both T-stubs

Component models
Component Models used: Tension zone

EC3-1.8 yield line patterns used to calculate the effective length of the equivalent T-stubs in the connection.

Column flange and flush endplate

Extended endplate

Group effects not automatically included (yet)
Component Models used: Compression Zone

Compression zone F-δ behaviour based on the work by Block and is defined by three parameters:

1. Initial stiffness,
2. Resistance,
3. Ductility,

linked with a curve-fit approach based on the stress-strain curve in EC3-1.2.
Comparison with 20 °C Tests by Girão Coelho

Beam: IPE 300
Column: HEM 340
Steel: S235
Bolts: M20 – 8.8

- Test
- Half bolt length
- Full bolt length to endplate

Endplate tp = 10 mm
Endplate tp = 15 mm
Endplate tp = 20 mm

Validation
Consideration of Temperature

- Temperature reduction factors after EC3 – 1.2 used in endplate, column flange, column web.

- Temperature reduction factors after EC3 – 1.2 – Annex D and Kirby used for the bolts

- The effects of cooling on the bolt material is ignored due to a lack of experimental data.

\[
T_{\text{connection}} = \alpha_{\text{connection}} \cdot T_{\text{connection}}
\]

Temperature effects

Temperature

- Temperature reduction factors after EC3 – 1.2 used in endplate, column flange, column web.

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\[
T_{\text{connection}} = \alpha_{\text{connection}} \cdot T_{\text{connection}}
\]
Comparison with High Temperature Tests

Flush endplate connection tests by Leston-Jones

Beams: UB 254x102x22
Column: UC 152x152x23
Steel: S235
Bolts: M20 – 8.8
Load level: 5, 10, 15, 20kNm
Temperature: 10 °C/min

Specimen

- Test
- Bolt rows individually
- Bolt rows as a group
Proposed Unloading at Constant Temperature

Massing’s hypothesis – unloading curve is double the loading curve

Load transfer between tension and compression zone
Proposed Unloading at Changing Temperature

Permanent displacement does not change with increasing temperature.
Permanent displacement does not change with increasing temperature.
Connection:
Flush endplate with two bolt rows
Load Ratio: 0.5
Heated to 550°C
Cooled to 20°C
Uniform temperature distribution

Graph showing predicted cooling behaviour:
- Temperature vs Rotation
- Spring Force vs Temperature

Graph elements:
- Upper bolt row
- Lower bolt row
- Compression zone
Preliminary Frame Study

- Three cases considered: Pinned, Rigid and Connection Element
- UDL on Beams and point loads on columns to a Load Ratio of 0.6
- Uniformly heated to 700°C and cooled to 20°C

Example

Beams: UB 254x102x22
Column: UC 203x203x71
Steel: S275
Bolts: M20 – 8.8
Preliminary Frame Study: Displacements

Failure temperature: 222°C in cooling
Failure component: Third bolt row

- Connection element
- Rigid
- Pinned

Connection rotation

Failure point of lower bolt row
Preliminary Frame Study: Internal Forces

Mid-span of beam

Connection

Temperature [°C]

Axial force [kN]

Moment [kNm]

Temperature [°C]
Preliminary frame study: Component Forces

Example

- Second bolt row
- Third bolt row
- First bolt row
- Upper compression zone
- Lower compression zone

Spring force [kN]

Temperature [°C]
Capabilities and Limitations of the Connection Element

- Flush endplate and extended endplate connections
- Up to five bolt-rows can be included
- Effective length of T-stubs calculated based on yield line pattern
- User defined temperature distribution for each component of the connection
- Cooling and unloading included
- Shear deformation in column-web and beam-end not considered
- Local flange buckling not considered
- No group effects for bolt rows included
- Bolt behaviour during cooling
Conclusion

• A component based connection element has been developed and implemented into Vulcan

• Good comparisons between the connection element and test results at ambient and elevated temperature could be found

• The new connection element gives a feasible way to include realistic connection behaviour in the global analysis of structures in fire

• Preliminary studies using the component-based connection element for endplate connections have shown:
  • Large residual forces within the connection during cooling
  • Moment reversal together with large axial forces can fail a connection in cooling

• Further component studies required to fill in the gaps

• More experiments on the cooling behaviour of bolts and frame structures needed
The Development of a Component-Based Connection Element for Endplate Connections in Fire

Questions ..?

Florian Block

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