

Full paper

Extending Component-Based Models to Full-Range Behaviour of Steel Joints

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Abstract

Component-based spring models developed according to the Component Method provide a practical alternative to advanced finite element (FE) models for predicting the behaviour of beam-to-column joints. However, inherent limitations of the EC3 analytical approach lead to joint characterisations that neglect key response features, including group effects, realistic shear distribution within the column web panel zone, and component stress interactions. Moreover, EC3 predictions are generally restricted to joint initial stiffness and plastic resistance, omitting strain-hardening effects and ductility capacity, which are essential for robustness-oriented structural design. This study extends a previously proposed Generalised Component-Based Model (GCBM) by incorporating post-plastic behaviour at the component level, including strain hardening and post-buckling response. The enhanced model enables prediction of joint ultimate resistance and rotation capacity. Validation against experimental and numerical results demonstrates satisfactory accuracy in reproducing the full-range response of beam-to-column joints subjected to bending and combined bending-axial loading. The proposed model provides a reliable and computationally efficient tool for simulating joint behaviour up to failure.

Keywords

Steel Joints, Component Method, Component-Based Models, Robustness

1 Introduction

Owing to its reduced complexity and reasonable accuracy, the Component Method of EN 1993-1-8 [1] (EC3) is widely regarded as a rational compromise between purely analytical [2], [3] and advanced Finite Element (FE) modelling [4], [5] approaches. In this context, component-based spring models [6], [7], developed in accordance with the Component Method, represent a practical alternative to advanced FE models when assessing the structural performance of beam-to-column joints.

Despite their practical advantages, the predictive capability of such models remains constrained by inherent limitations of the Component Method. In particular, several critical features influencing joint response are neglected, including group effects, the effective shear height of the column web panel, and stress interactions between individual components. These simplifications may lead to inconsistencies with the current understanding of joint behaviour.

To address these shortcomings, a Generalised Component-Based Model (GCBM) was previously developed, incorporating group effects and a more realistic representation of the panel zone. Validation against experimental evidence and EC3-based analytical predictions demonstrated the model's reliability in estimating the initial stiffness and plastic resistance of beam-to-column joints [8].

Nevertheless, EC3-based predictions remain limited to these two parameters, providing only an idealised representation of joint behaviour. The absence of strain-hardening effects and ductility supply prevents their direct application in robustness-oriented design scenarios, where accurate simulation of the full-range joint response is essential.

The present work extends the previously developed GCBM by incorporating the post-plastic response, namely material strain-hardening for components subjected to shear, bending, and tension, together with post-buckling behaviour for compression-controlled basic components. This extension enables the estimation of joint ultimate resistance and rotation capacity. Comparative analyses against experimental and numerical data demonstrate the model's satisfactory predictive capability for the full-range

behaviour of joints subjected to pure bending as well as combined bending and axial loading. The proposed model therefore provides a reliable and computationally efficient framework for simulating joint response up to failure, provided that the mechanical properties of the individual components are characterised with adequate accuracy.

2 Overview of the Generalised Component-Based Model

The Generalised Component-Based Model (GCBM) [8] was initially developed as an alternative to the EC3 Component Method, which relies on an analytical assembly procedure to determine the plastic resistance and initial rotational stiffness of steel joints. As illustrated in Fig.1. the GCBM represents the individual connection rows (i.e. tension and compression rows) by means of equivalent extensional springs (K_i) with behaviour laws derived from the mechanical properties of all potentially active components acting in series at the level of each row.

In addition to the row springs, the model incorporates rigid-plastic fuse elements that simulate the development of group mechanisms between connection rows subjected to tension (i.e. bolt rows). Once the resistance of these initially rigid fuse elements is attained, the tensile force transmitted by the bolt rows belonging to the activated group is capped by the corresponding group resistance. Under increasing external loading, this modelling strategy enables internal plastic redistribution governed by the individual and group resistances of the connection rows until equilibrium is achieved. This redistribution mechanically reproduces the EC3 analytical procedure used to account for group effects, while allowing for direct simulation within a mechanical modelling framework.

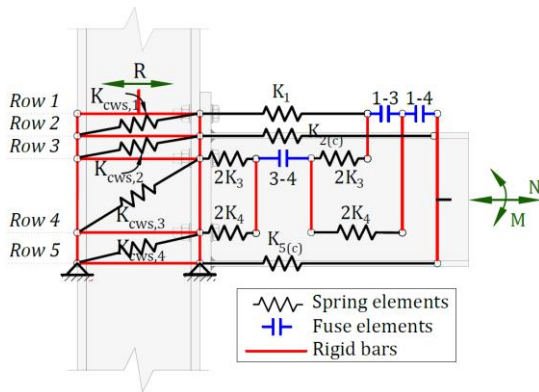


Figure 1 General view of the GCBM applied to a single-sided beam-to-column bolted joint

Unlike the simplified EC3 representation of the column web panel in shear as a single component subjected to uniform shear, the GCBM discretises the column panel zone into $(n-1)$ shear subpanels, where n denotes the number of connection rows. In addition, the shear resultant R acting on the column above the joint region is explicitly introduced. This formulation allows the model to capture the non-uniform distribution of shear forces over the height of the panel zone by simultaneously accounting for the column shear resultant R and the forces F_i transmitted by the connection rows.

The mechanical formulation of the GCBM is fully consistent with the theoretical basis of the EC3 Component Method.

Consequently, as demonstrated in [8], when the properties of components (stiffness and resistance) calculated with the EC3 analytical formulae are assigned to the model's extensional springs, the GCBM provides EC3-compliant predictions.

However, the model presents clear advantages over the normative approach. First, it enables direct prediction of the joint moment-rotation ($M-\phi$) curve without resorting to intermediate analytical operations typically required by the normative approach. Second, the model explicitly incorporates group mechanisms developing in plate components subjected to transverse bolt forces. Third, it captures a realistic shear force distribution within the column web panel zone active in shear. Finally, as a perspective, the GCBM provides a consistent framework for incorporating stress interactions within column web components. Moreover, by explicitly modelling all potentially active joint components, the model enables consistent characterisation of joint response under complex loading histories, including bending moment sign reversals (e.g., transitions between sagging to hogging) and combined bending and axial force loading.

Building upon these capabilities, the possibility to extend the applicability of the GCBM to predicting the full-range behaviour of structural joints is not a farsighted objective, and in the following sections, a simple way to characterise the behaviour of beam-to-column joints up to failure is presented for joints subjected to bending and combined bending-axial force actions.

3 Characterisation of components

Similar to the Component Method of EC3, the reliability of the GCBM is highly dependent on the accuracy of components characterisation. In this regard, the stiffness, the strength, and the deformation capacity of components may be derived using various techniques with different levels of accuracy and complexity such as experimental testing, numerical simulations, and analytical methods. This step enables the definition of force-deformation ($F-\Delta$) curves that can be assigned to the extensional springs simulating the components (connection rows and column panel) within the GCBM.

Prior to their actual characterisation, the active joint components are identified based on the loading type acting upon them as follows:

- i) *Compression*: column web in compression (CWC) and beam flange in compression (BFC)
- ii) *Tension*: column web in tension (CWT), column flange in bending (CFB), endplate in bending (EPB), bolts in tension (BT), beam web in tension (BWT)
- iii) *Shear*: Column web panel in shear (CWS).

3.1 Elastic response of components

Within the elastic range of response, EC3 provides a set of analytical formulae for deriving the plastic resistance $F_{R,pl}$ and elastic stiffness K_i (equal to EK_i) of basic joint components.

Table 1 summarises the standard characterisation of the most frequently encountered joint components in typical

beam-to-column joint configurations. These formulae enable the direct definition of an elastic-perfectly plastic force-displacement ($F-\Delta$) curve for each joint component. Accordingly, the components are assumed to deform elastically until their plastic resistance is attained.

Table 1 Characterisation of basic active components according to EC3

Comp.	Plastic resistance	Stiffness coefficient
CWS	$V_{wp,pl} = \frac{0.9f_{y,wc}A_{vc}}{\sqrt{3}\gamma_{M0}}$ $F_{c,wc,pl} = \frac{\omega k_{wc} b_{eff,c,wc} t_{wc} f_{y,wc}}{\gamma_{M0}}$	$k_1 = \frac{0.38A_{vc}}{\beta z}$
CWC	but $F_{c,wc,pl} \leq \frac{\omega k_{wc} \rho b_{eff,c,wc} t_{wc} f_{y,wc}}{\gamma_{M1}}$	$k_2 = \frac{0.7b_{eff,c,wc} t_{wc}}{d_c}$
CWT	$F_{t,wc,pl} = \frac{\omega b_{eff,t,wc} t_{wc} f_{y,wc}}{\gamma_{M0}}$	$k_3 = \frac{0.7b_{eff,t,wc} t_{wc}}{d_c}$
CFB	Equivalent T-stub model	$k_4 = \frac{0.9l_{eff} t_{fc}^3}{m^3}$
EPB	Equivalent T-stub model	$k_5 = \frac{0.9l_{eff} t_p^3}{m^3}$
BFC	$F_{c,fb,pl} = \frac{M_{c,Rd}}{h - t_{fb}}$	$k_7 = \infty$
BWT	$F_{t,wb,pl} = \frac{b_{eff,t,wb} t_{wb} f_{y,wb}}{\gamma_{M0}}$	$k_8 = \infty$
BT	$F_{t,pl} = \frac{0.9f_{ub}A_s}{\gamma_{Mb}}$	$k_{10} = \frac{1.6A_s}{L_b}$

However, to account (to a limited extent) for material non-linearities, EC3 makes a distinction between the elastic (M_{el}) and plastic joint moment resistance (M_{pl}) by defining a $M_{el}=2/3M_{pl}$ limit for the onset of plasticity within joint components. This limit can be directly applied at component level by defining an elastic resistance F_{el} corresponding to $2/3F_{pl}$.

Provided that neither a brittle failure, nor instability phenomena occur, the plastic deformation of components is not limited by an explicit ductility criterion. Therefore, the plastic plateau is assumed to be virtually unlimited.

These considerations allow the definition of simplified tri-linear laws for joint components, accounting for an initial stiffness K_i , an elastic resistance F_{el} , a post-elastic stiffness $K_i/7$, and a plastic resistance F_{pl} , as shown in Fig. 2.

3.2 Post-plastic response of components

In general, assuming elastic-perfectly plastic behaviour laws for joint basic components leads to conservative predictions of overall joint behaviour. In this framework, material strain-hardening and membrane effects are disregarded. Thus, the post-plastic behaviour of the joints is characterised by a plateau without a clearly defined rotation capacity limit. To account for these effects, simplified analytical relationships have been proposed for the characterisation of the post-plastic response of joint components [7], [9], [10].

Simoes da Silva et al. [9] determined typical ranges for the post-plastic stiffness K_{p-pl} of various basic joint components commonly employed in bolted beam-to-column joints. Based on a calibration against experimental results, the authors concluded that K_{p-pl} may vary between 0.1% to 4.6% of the initial stiffness K_i for components subjected

to tension or shear.

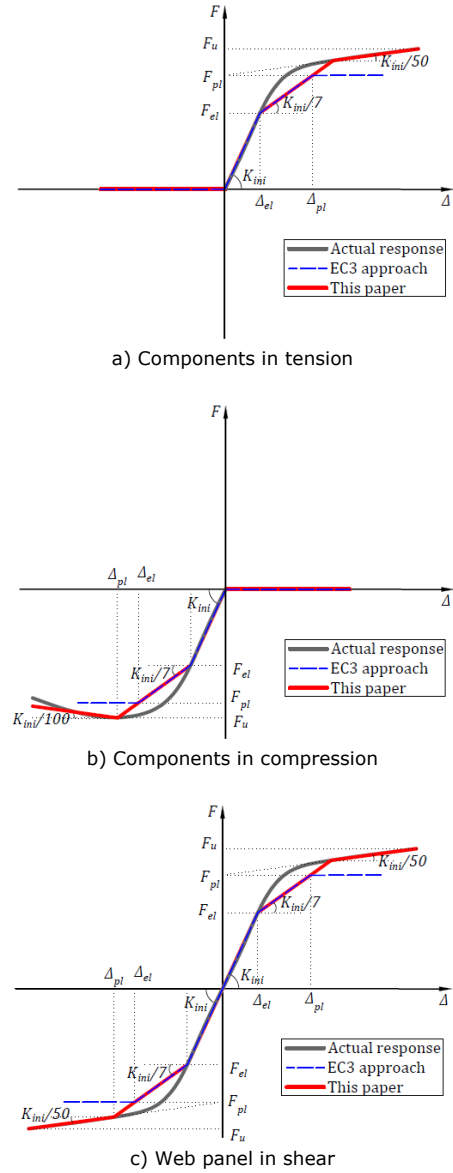


Figure 2 Typical behaviour laws for basic joint components

Following a similar approach, Jaspart et al. [10] proposed estimating the post-plastic stiffness of basic components as 2% of K_i for components subjected to compression and tension. It is worth noting that the 2% value proposed in [10] is not a merely arbitrary limit, as it attempts to capture the strain-hardening modulus the $\sigma-\epsilon$ steel material curve. Furthermore, this value falls within the variation range identified by Simoes da Silva et al. [9].

Additionally, these authors suggest evaluating the components' ultimate resistance by simply substituting the yield strength of steel f_y with the ultimate strength f_u in the formulae listed in Table 1. As a result, the full non-linear response of components may be represented through simplified tri-linear $F-\Delta$ curves describing both the elastic and the post-plastic behaviour, as illustrated in Fig. 2. Therefore, component ductility – treated solely from a qualitative standpoint in the present version of EC3 – becomes a quantifiable parameter.

In this paper, the 2% K_i limit for the post-plastic stiffness has been adopted for components subjected to tension

(CWT, CFB, EPB, BWT) and shear (CWS). Additional assumptions were made for the ultimate resistances of BT, EPB, and CFB components, as described below.

For BT, the ultimate resistance F_u was estimated by removing the 0.9 reduction factor from the analytical expression given in Table 1. For the EPB and CFB components, as long as the component's ultimate failure mode corresponds to a Mode 1 or Mode 2 failure as per the equivalent T-stub model of EC3, replacing the f_y with f_u in the formulae listed in Table 1 does not necessarily provide sufficiently accurate results.

As highlighted by Lyu et al. [12], among others, this simplified assumption may lead to overconservative predictions, underestimating the T-stub ultimate resistance by 34% on average, as it neglects additional resisting mechanisms (e.g., catenary action in the T-stubs plates) activated during the post-plastic range of response.

For this reason, in the present study, the F_u of the EPB and CFB components was limited by the bolt-row ultimate resistance (i.e., Mode 3). Although this may appear as an oversimplification, this assumption led to reasonable accuracy in predicting the full-range behaviour of the joints analysed herein.

For the column web in compression (CWC), the model proposed by Jaspart et al. [13] was adopted, as it enables the estimation of the ultimate resistance of CWC with account for instability (buckling) phenomena. In addition to this analytical model, a post-buckling stiffness was considered in this paper. This softening branch of the response (see Fig. 2b) is characterised by a negative stiffness estimated at 1% of K_i calibrated against experimental results reported in [13], [14].

4 Validation and performance of the GCBM

The proposed model was previously validated in [8] with a view to proving its code-compliance by performing direct comparisons with the Component Method of EC3. Given that that the EC3 behaviour laws introduced hereabove in 3.1 were used for characterising the basic joint components, the GCBM provided highly consistent predictions with those obtained using the EC3 approach.

In the present study, the validation is extended by incorporating the post-plastic response of the components within the GCBM.

For the validation process, the GCBM was numerically implemented in the Finelg software [15] as a macroelement dedicated to joint modelling.

4.1 Joint response under bending moment

The results reported in Fig. 3 show a very good agreement between the predicted and experimental $M - \phi$ curves for both bolted (RJ, EPB, CFB) and welded joints (CWC) tested in [14]. It's noteworthy that this experimental campaign is particularly relevant for the validating the GCB, as the test specimens were designed such that a single joint component governs the plastic resistance and, to a large extent, the post-plastic behaviour of the overall joint (i.e., endplate in bending for the EPB specimen, column flange

in bending for the CFB specimen, and column web in compression for the CWC specimen). These governing failure modes are also correctly predicted by the GCBM.

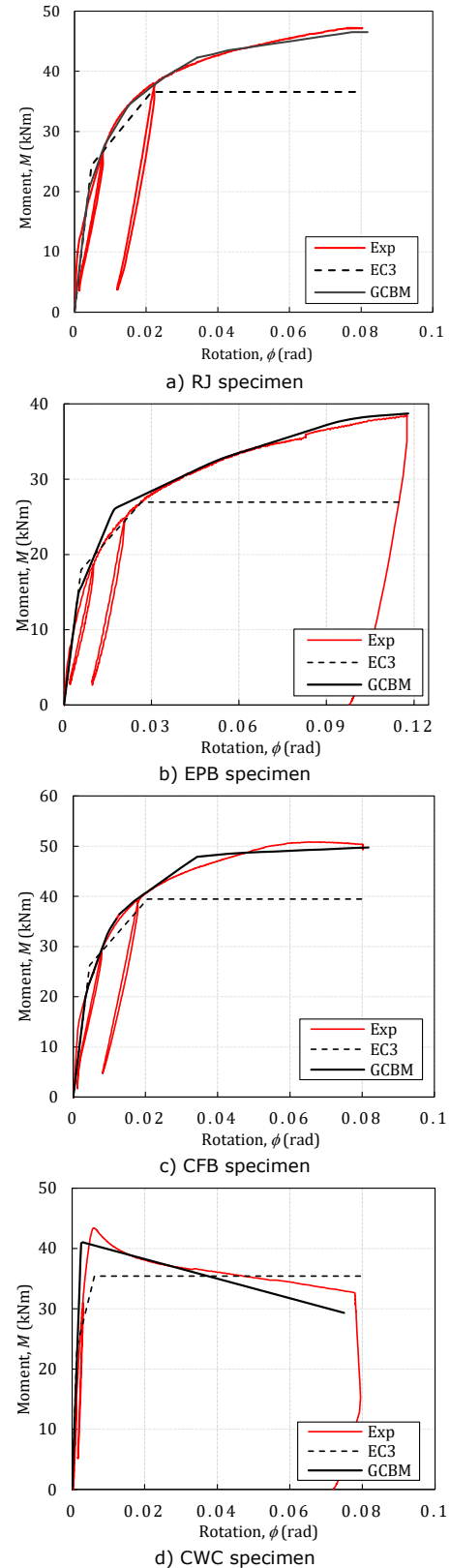


Figure 3 Comparison of results in terms of $M - \phi$ curves between experimental testing (Exp), Eurocode 3 approach (EC3), and the GCBM predictions for beam-to-column joint specimens tested in [14]

The very good match between the experimental results and the GCBM predictions indicates that the assumptions made on component modelling introduced in the previous

sections are appropriate. Furthermore, the prediction obtained for the RJ specimen (Fig. 3a) provides additional support for this conclusion. During testing, the RJ specimen exhibited progressive plasticity involving multiple joint components, and the numerical response provided by the GCBM indicates a similar trend.

Similar observations can be made for the joint specimens tested in [16]. The overall shape of the $M - \phi$ curves (see Fig. 4), as well as the main characteristics of the joint response in terms of initial and post-plastic stiffness, plastic and ultimate resistance are well captured by the GCBM. In addition, the failure modes associated with the ultimate resistance of the tested joints are also in line with experimental observations (i.e., CWS for the O1 specimen, and CWC for the O13 specimen).

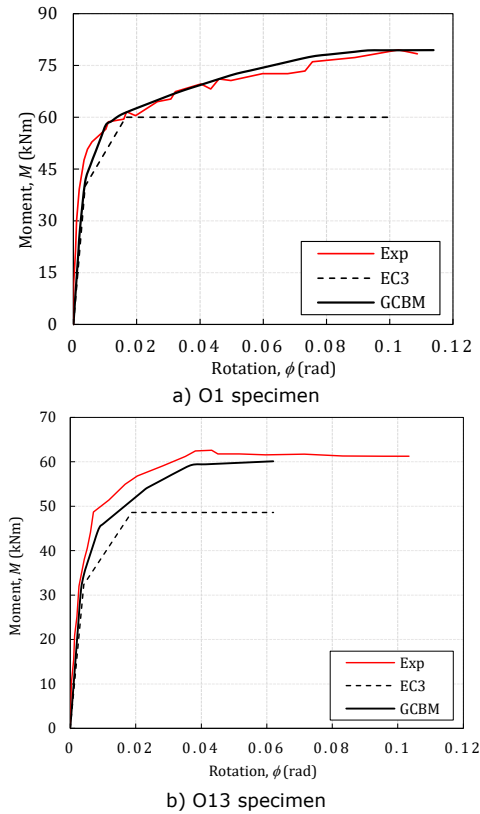


Figure 4 Comparison of results in terms of $M - \phi$ curves between experimental testing (Exp), Eurocode 3 approach (EC3), and the GCBM predictions for beam-to-column joint specimens tested in [16]

4.2 Joint response under combined bending moment and axial force

The performance of the GCBM was further assessed using an experimental test conducted by Kozłowski and Kukla [17] on an extended endplate double-sided joint (P4-10 specimen) subjected to combined bending moment (M) and axial force (N) – conditions mimicking a column loss.

The test specimen was modelled in the Finelg software [15] using the GCBM macroelement in combination with classical beam elements simulating the joint region and the connected beams respectively.

The actual material properties reported in [17] were used for defining the behaviour laws assigned to both the spring elements within the GCBM and the beam elements. The

boundary conditions described by the authors were reproduced by introducing extensional springs with a stiffness of 225 kN/mm at the model extremities to account for the axial stiffness of the lateral supports.

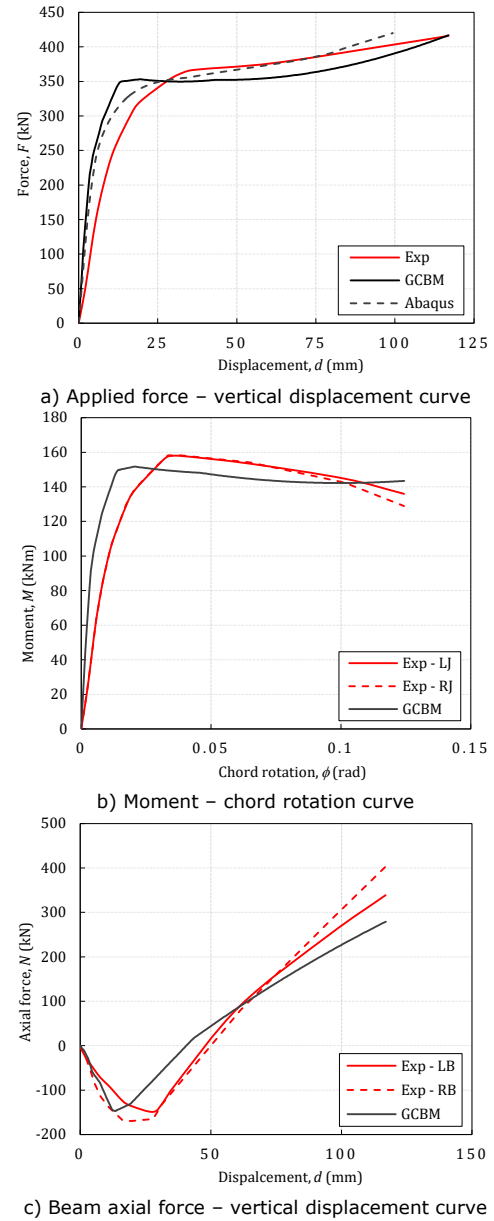


Figure 5 Comparison of results for beam-to-column joint specimens tested in [17]

Fig. 5a presents a comparison between the GCBM prediction and the experimental applied force – vertical displacement ($F-d$) curve. A noticeable discrepancy between the numerical and experimental elastic stiffness is observed.

To identify the source for this discrepancy, an advanced FE model (see Fig. 6) was built using Abaqus CAE [18]. The good correlation between the predictions of both simplified GCBM and advanced FE (Abaqus) models indicates that the initial stiffness of the experimental $F-d$ curve may have been influenced by fitting and settlement of the specimen within the testing rig during the loading phase.

These observations are further supported by results reported in [19], where advanced numerical simulations of the experimental tests performed in [17] consistently predict stiffer responses than those observed experimentally.

Despite this inconsistency, however, the GCBM provides a reasonable prediction in terms of overall $F-d$ curve (Fig. 5a), the evolution of the joint bending moment with respect to the chord rotation (LJ and RJ for the left and right joints in Fig. 5b), and for the development of membrane forces in the beams of the specimen (Fig. 5c).

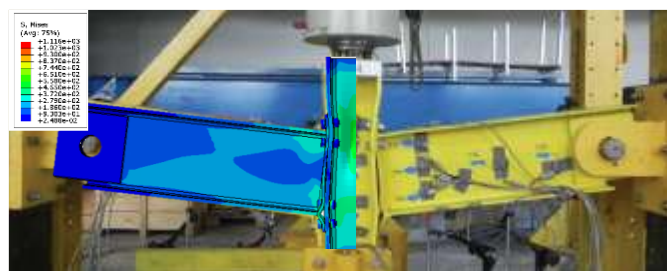


Figure 6 Numerically predicted failure (Abaqus) and real deformation observed at failure for the P4-10 test specimen [17]

In column loss scenarios, the beam-to-column joints are key structural components that enable the system to bridge over the lost column while undergoing large displacements. The latter introduce significant second order effects manifested through the development of membrane forces within the connected beams. As it can be seen in Fig. 5c, the GCBM captures this phenomenon, and predicts, with satisfactory accuracy, the development of both compressive arching and catenary actions.

The discrepancies between the experimental response and predictions can be partly attributed to the pronounced asymmetric response during testing, including in-plane column tilting and differences in axial forces between the left and right beams (LB and RB in Fig. 5c).

5 Conclusions

This study presented an extension of the Generalised Component-Based Model (GCBM) to enable prediction of the full-range behaviour of beam-to-column joints. The proposed model incorporates strain-hardening effects and post-buckling response at the level of basic joint components, allowing the estimation of joints' ultimate resistance and rotation capacity. The modelling framework remains fully compatible with the theoretical background of the EC3 Component Method while overcoming its inherent limitations regarding post-plastic behaviour.

Validation against experimental results demonstrated that the GCBM accurately reproduces the moment-rotation response, failure modes, and progressive plastic redistribution in joints subjected to bending. Additional comparisons under combined bending-axial loading confirmed the capability of the model to capture membrane effects and load redistribution mechanisms relevant to robustness-related scenarios.

Despite its simplified formulation, the model provides predictions comparable to advanced FE analyses while maintaining low computational demand. The proposed approach therefore represents a reliable and efficient tool for

performance-based joint assessment up to failure.

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