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# Semi-Rigid connections in steel structures: State-of-the-Art report on modelling, analysis and design

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**Abstract.** In the structural analysis of steel frames, joints are generally considered as rigid or hinged considering their moment transfer ability. However, the first studies conducted with the beginning of the 20th century showed that the joints do not actually fit these two definitions. In reality, a joint behaves between these two extreme points and is called semi-rigid. Including the actual state of the joint in the structural analysis provides significant economic advantages, so the subject is an intense field of study today. However, it does not find enough application area in practice. For this reason, a large-scale literature published from the first studies on the subject to the present has been examined within the scope of the study. Three important points have been identified in order to examine a joint realistically; modelling the load-displacement relationship, performing the structural analysis and how to design. Joint modelling methods were grouped under 7 main headings as analytical, empirical, mechanical, numerical, informational, hybrid and experimental. In addition to the moment-rotation, other important external load effects like axial force, shear and torsion were considered. Various evaluations were made to expand the practical application area of semi-rigid connections by examining analysis methods and design approaches. Dynamic behaviour was also included in the study, and besides column-beam connections, other important connection types such as beam-beam, column-beam-cross, base connection were also examined in this paper.

**Keywords:** semi-rigid; steel connection; moment-rotation; frame analysis; steel design; joint modelling

## 1. Introduction

The selection of the structural system plays a major role in the design and cost of a structure. Similarly, the type of joint in steel structures is also of great importance. As it is known, two connection types were initially considered while designing steel frames: rigid and pinned joints. The use of the ideally pinned state means that no moment can be transmitted between the beam and the column. Connections have no rotational stiffness and cannot transmit moments in pinned joints. Besides, fully rigid joints have rotational capability and can transfer all kinds of loads between beam and column. But, studies show that these approaches are not correct. While many connections that are considered rigid rotate a little under the moment, connections that are considered to be hinged can transmit a certain amount of moment. This case is defined as a semi-rigid joint. Since the flexibility of a joint will significantly affect the displacement of the structure and the distribution of the internal forces; the behaviour of semi-rigid joints has been intensively studied since the first quarter of the 20th century.

Studies carried out until the 1950s consist of pioneering experiments and analytical studies on the subject. After this date, the speed and variety of studies have increased as a result of important developments in the steel construction sector such as the spread of electronic calculators and computers, the popularization of matrix methods and finite element methods, and the transition from rivet to bolt. In the previous studies, the developments up to this date were examined. Some good studies should be highlighted (Jones *et al*. 1983, Diaz *et al*. 2011, Ivanyi *et al*. 2000, Baniotopoulos *et al*. 2000, Maquoi *et al*. 1991). The scope of the study focused on the innovations and developments in semi-rigid connections after 1980, especially in the 21st century.

Starting in the 1930s with the slope-deflection equation and moment distribution methods, the 1960s with the matrix stiffness methods, and nowadays, with complex iterative analysis methods coupled the structural analysis with that of the joint. All these important developments have played an important role in the understanding and development of semi-rigid connections.

The actual behaviour of a joint can be understood by performing a global analysis of the structure using the moment-rotation curve (see Fig. 1). This process needs to determine the mechanical properties of the joint in terms of its rotational stiffness (Kj), moment resistance (Mj, Rd), and rotational capacity (φCd) starting from their geometrical and material properties.

Multiple models can be applied to determine the mechanical behaviour of joints such as analytical,

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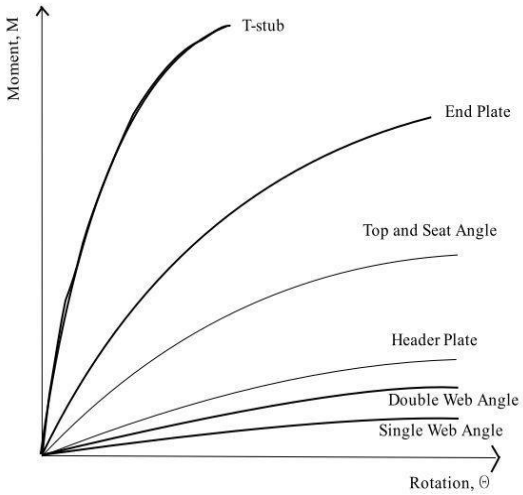



Fig. 1 Moment-Rotation Curves of Common Semi-Rigid Connection Types

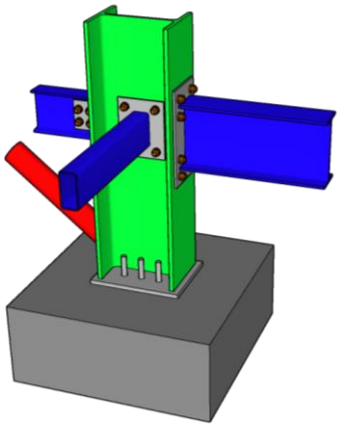


Fig. 2 An Example of 3D Connection Detail. (Including Minor-Major Axis, Brace and Base Connection)

empirical, experimental, informational, mechanical, and numerical. Detailed explanations about all these approaches will be given below in the text.

Joints are of great importance in frame structures. These connections can be column-column, beam-beam, splice, column-beam, column-beam-brace, and column-foundation. Joint details and characteristics vary according to the connected element types. Although studies on semi-rigid connections mostly focus on beam-column connections, studies on other connections have shown that the rigid-joint assumption is not valid in these connections either. Therefore, within the scope of this study, all the connections of primary elements were taken into account. In this study, priority was given to common joint types.

For practical calculations of semi-rigid connections, knowledge is needed in three basic areas. These are the moment-rotation characteristic of the joint, the matrix-finite element formulations, and the design method. These three issues were examined under separate headings in this study.

Finally, within the framework of the studies, it was seen that the behaviour of the joints is not isolated; also, it is significantly affected by the elements, frame, and load conditions. In reality, a joint behaves in 3 dimensions (see figure 2). Here, there are 6 basic stress-strain parameters for a joint. It is under influences such as axial force, shear force, in-plane bending, and out-of-plane bending. Therefore, not only the moment-rotational relationship but also other strength states should be taken into account in the joint. In this study, moment-rotation, moment-axial force and/or shear force interaction, axial force-displacement, shear force-displacement, out-of-plane bending, torsion, and minor-major axis joints are considered, with respect to monotonic and dynamic load conditions.

## 2. Modelling the moment-rotation relationship

To include joint flexibility in structural analysis, the moment-rotation relationship must be determined. Various methods developed to do this have been presented in previous studies. These methods were categorised by the authors considering the way of obtaining the moment-rotation relationship. Accordingly, the methods were divided into 7 groups and are; analytical, empirical, mechanical, informational, numerical, experimental and hybrid methods. Similar classifications were made in other studies (Diaz *et al.* 2011). Each method is explained under its heading.

### *2.1 Analytical methods*

Analytical methods are obtained by using relations such as compatibility, load-displacement relation within the outline of general engineering mechanics of the joint characteristic. This method was first used by Beafoy and Moharram (1948) to determine the moment-rotation relationship of web-cleat joints by using existing experimental data on force-deformations of angle segments. Lewitt *et al.* (1969) took into account the angle component in the tension region. Yee and Melchers (1986) modelled end-plate joints with the t-stub analogy, taking account of various deformations and failure modes. Richard *et al.* (1988) modelled the moment-rotation relationship with a 4-parameter function by using the rigid bar-deformational spring analogy and experimental data. Youssef-Agha *et al.* (1989) also modelled the moment-rotation relationship of top-and-seat-angle joints with an analytical model, which includes deformation of column flange, angles and bolts. Kishi and Chen (1990) modelled angle connections as a power function. Initial stiffness and moment capacity as the independent variables in the function were found by analytical methods. Shape factors were determined for curve-fitting using databases and the least-square method. Kukreti and Abolmaali (1999) proposed an analytical model that could represent the hysteresis behaviour of top-and-seat-angle joints. The model was obtained by generalizing 12 experiments with regression analysis, taking into account 4 different dynamic models. Shen and Astaneh-Asl (2000) constructed the hysteric model of bolted-angle joints using finite fibre elements. Bolt-slip was included in the model. Three important regions detected in the hysteric behaviour

of bolted-angle joints were modelled as three-linear. Da Silva *et al*. (2000) proposed an analytical method for the behaviour of joints under bending. The proposed method was obtained by elastic post-buckling analysis and since it was in closed form, the entire curve of the joint was modelled without iteration. Mofid *et al*. (2001) developed an analytical model on semi-rigid steel joints. This process was about plate theory, and the bi-linear curve was obtained. It was sufficient to know the material properties and geometry for the curve. However, the study was not extended to cover the non-linear part. In another study, a bilinear model was adopted to determine the exact behaviour of the end-plate connections (Mohammadi-Shooreh 2004). Initial and ultimate stiffness were determined with analytical methods. Also, maximum moment capacities of connections, beams, and columns were considered. Shi *et al*. (2007) obtained the moment-rotation relationship of stiffened extended end-plate joints by superposing the moment-shear rotation and moment-gap rotation curves obtained by analytical methods. Shi *et al*. (2007) proposed a bi-linear method for the hysteric moment-rotation curve of end plate joints. Here, the variables were yielding moment, ultimate moment and their corresponding rotation values. Davaran *et al*. (2019) obtained the moment-rotation relationship within the framework of the elastic-plastic analysis of bolted angle joints. Another analytical method was proposed to examine joints regardless of loading and profile type by Obeydi *et al*. (2020). The method was bi-linear, and the post-limit stiffness and elastic stiffness values were determined by the component method. These studies considered beam-to-column joints.

Base connections also play a significant role the behaviour of a structure. For modelling the moment-rotation relationship of base plates, Ermopoulos and Stamatopoulos (1996) provided the first work based on general mechanics principles. By taking the model as a reference, the moment-rotation relationship under cyclic loads was also obtained (Ermopoulos and Stamatopoulos 1996, Stamatopoulos and Ermopoulos 2011). Kanvinde *et al*. (2012) developed a new method that considers eccentricity for the rigidity of base-plates. The study was carried out considering dynamic loadings. The moment-rotation relationship of deeply embedded column base plates is different from that of end plate joints or standard column base plates. Rodas *et al*. (2017) proposed a model in which moment-rotation can be calculated with hyperstatic system solution using the Winkler beam. Krystosik (2018) similarly used the elastic half-space and boundary element method as well as the Winkler model.

Analytical models have also been studied under different profile types and joint types. Ghobarah *et al*. (1996) established the moment-rotation relationship of end plate blind bolted connections connected to box columns. Liu and Astaneh-Asl (2004) pointed out the moment-rotation relationship of shear tab composite joints based on experiments and mechanical knowledge. With this approach, the moment-rotation relationship can be established with or without slab. Loh *et al*. (2006) examined the effect of partial shear connection in composite flush end plate joints. The behaviour was modelled by the analytical method and the moment-rotation curves with the proposed method correlated well with the experiments.

Another important type of connection in steel structures is column-beam-brace connections. Such combinations are usually formed with a gusset plate, and Stoakes and Fahnestock (2012) obtained the hysterical moment-rotation curve of this type of joint. Wang *et al*. (2018) examined hollow section beam-to-column extended end plate joints. The important aspect of the method was the consideration of strain hardening. Parameters in the model were; stiffness and moment values of the joint.

Eccentricity was not taken notice of in the developed methods. However, under the influence of various architectural conditions, the joints are built eccentrically. Shi and Fan (2018) analytically examined eccentric joints formed from box profiles. The operation was limited by elastic stiffness. Zhao *et al*. (2020) used yield-line theory to obtain the full behaviour of this type of connection. Loureiro *et al*. (2013) studied the 3D behaviour of joints connected to the minor axis of columns, which is called E-stub, with FEM (finite element method). The authors proposed a 3D FEM and analytical model for joints connected to the minor axis by end plate. The model was generated by taking the joint as the equivalent frame. Lopez *et al*. (2021) examined additional plate configuration in flush end plate beam-to-beam joints with the equivalent frame analogy.

### *2.2 Empirical methods*

Empirical methods are the mathematical formulation of moment-rotation data using a range of methods such as regression analysis. Data can be obtained by methods like experiments and parametric studies and standardized by various methods. The first applications of the method were proposed by Sommer (1969) and Kennedy (1969). Frye and Morris (1975) modelled the moment-rotation relationship of diverse joints with odd-power. In this method, only the joint was taken into account and it was assumed that the other elements behave linearly. Krishnamurthy *et al*. (1979) proposed a method based on parametric studies. In the method, the necessary parameters for establishing the moment-rotation relationship were determined through the joint material properties and geometric properties. Kukreti *et al*. (1987) expanded the work of Krishnamurthy *et al*. (1979) to include flush end plate joints with a new parametric study. In these proposed methods, moment-rotation curve can take negative values for some moment values. Jones *et al*. (1981) performed a new study based on Cubic B-Spline. Although it could solve the problem, it needed many data. Azizinamini and Radziminski (1989), using a different approach to solve the negative value problem, obtained the monotonic moment-rotation relationship of top-seat-web-angle joints. Wu and Chen (1990) developed the moment-rotation curve as an exponential function using data banks. The proposed method depends on 3 basic parameters, which were initial stiffness, moment capacity and shape factor. The study was limited to joints with angles. The model was developed for

top-and-seat-angle connection with or without web angles. Attiogbe and Morris (1991) used Goldberg-Richard and experimental data using the finite difference method proposed a 4-parameter moment-rotation curve. The 4 parameters were based on the joint geometry. The procedure was limited to double web angle joints. Bahaari and Sherbourne (1997) studied end plate connection. The moment-rotation relationship was generalised using numerical study results and Richard-Abbott power function. The remarkable feature of this model was being independent of the location of the plastic hinge. Chisala (1999) proposed a new three parameter exponential model to describe the full behaviour of connection. In the method, the moment-rotation curve was divided into 3 regions as initial region, strain-hardening region and plastic yielding region. Parameters can be obtained by the component method. Hong *et al*. (2002) modelled the moment-rotation relationship of double angle connections with 3D FEM. The generalised relationship was easily established by performing the regression analysis with the results of the numerical analysis using the Richard formula. Lee and Moon (2002) proposed a 2-parameter logarithmic model for the moment-rotation relationship of joints with angles. In the model, the parameters were shape parameters and were used for curve–fitting. Kishi *et al*. (2004) suggested a model for the moment-rotation curve with a 4-parameter power function. Here, the moment-rotation relationship was established with initial stiffness, strain-hardening stiffness, reference joint moment and shape parameter. Abolmaali *et al*. (2005) constituted an empirical method for flush end plate joints based on Ramberg-Osgood and three-parameter power models and various experiments and numerical solutions. The method was supported by regression analysis. As a result of the study, a good correlation was found between the experiments and the model. Abolmaali *et al*. (2009) experimentally investigated the behaviour of various semi-rigid connections under dynamic loading. Experiments were performed by curve-fitting with the 3-parameter Ramberg-Osgood function. The four-parameter power model for seat angle joints was studied by Ahmed (2017). In this work, prying force was taken into account. Ahmed and Kishi (2017) also interested with the revised model proposed by Kishi and Chen (1990).

Soleimani and Behnamfar (2017) developed a method called tangent inverse equation for welded joints. Variables of the equations were initial stiffness, post-elastic stiffness and reference moment. Parameters were determined by a data set derived from numerical studies with the semi-analytical method. Kong and Kim (2017) proposed a new model for a single web angle. In the model, parameters were determined directly from the material and geometric properties. For two different failure modes, two different formulations were used as hyperbolic sine and tangent functions. The study was adapted to top-and-seat angle joints later by Kong and Kim (2017).

The dynamic models developed are generally tri-linear, which causes sharp turns in the curve. This constitutes a deviation from the real situation. To overcome this, Al-Bermani *et al*. (1994) proposed a 4-parameter hysterical model. 4 parameters were initial stiffness, bounding stiffness, elastic moment capacity and, bounding moment capacity. These values can be obtained from the appropriate database or through analytical methods. Although the data used for the dynamic moment-rotation curve come from cycle experiments or parametric studies, Zapico-Valle *et al*. (2012) showed that dynamic stiffness can also be found by correlation of modal parameters. Mohammadi-Shooreh *et al*. (2013) used logarithmic linear regression analysis for beam-to-beam flush end plate joints. Smitha and Kumar (2013) standardised the data obtained from parametric studies of flange plate composite joints with the Kishi-Chen 3-parameter power model (Kumar and Smitha 2013). Nassani (2014) generalised cap plate combinations with a modified Richard-Abbott function. Yang *et al*. (2014) worked on double split tee combinations with the Richard-Abbott function.

Single web angle joints are generally accepted as hinged and have not been sufficiently addressed in the literature. Kong and Kim (2015) compiled the numerical study results and proposed two different hyperbolic functions corresponding to different failure modes. Existing methods may not be sufficient for angle joints, because such joints are delicate and many force effects must be considered together. Therefore, Prabha *et al*. (2015) introduced a new approach by modifying the Frye-Morris Method for double angle connections.

Empirical methods developed to date are only on joints and do not take into account 3D behaviour. In contrast, Diaz *et al*. (2018) generalised the end plate joints by fitting with the sextic polynomial equation; using FE analyses and experiments in the literature. In the method, the interaction between the minor axis and the major axis was also considered, and attention was paid to the location of the joint area in the structure. Gao and Guo (2018) modelled composite flush end plate joints with power function and linearization. In the proposed method, stiffness reduction was also taken notice of and was independent of loading and joint configuration. Liu (2019) conducted a study on the shape parameter of extended end plate joints in 3-parameter power models. The Author proposed an alternative to shape parameters by comparing 3D FEM with experimental data.

Empirical studies focus on connections of I profiles. When it is desired to examine the combinations of elements formed from other profiles, these methods does not yield results. For this, Lee *et al*. (1993) proposed a method for box column-I beam connections. The experiments were standardised with the Ramberg-Osgood function. Rao and Kumar (2006) performed the parametric study on RHS (rectangular hollow section) beam-to-column connection with web opening. The authors suggested a method to draw moment-rotation behaviour of that kind of connection. The method was generated by three-parameter power models (Kumar and Rao 2006).

Empirical methods are also favourable for connections other than steel beam-to-column types. Ermopoulos and Stamatopoulos (1996) proposed a simple equation for the moment-rotation curve of base plates. Ngueiro *et al*. (2009) developed a model based on databases for the cyclic moment-rotation relationship of end-plate composite joints. Abdollahzadeh and Ghobadi (2014) studied a new

polynomial model for base-plates in which deformation characteristics were supported by mechanical methods. Gang and Caiqi (2021) studied flower gusset composite joints, considering axial forces and bolt clearance. Power function was employed and shape parameter was determined from numerical studies. Pan *et al*. (2021) utilised the 3 parameter power function proposed by Kishi and Chen (1990) and studied exposed column base connections under seismic loading.

### *2.3 Mechanical methods*

Mechanical methods, which can be summarised as representing the load-deformation relationship of the joint with deformable elements and rigid bars, occupy an important place in obtaining the moment-rotation relationship of the joint. If important components of the load-deformation relationship are detected, the relationship can be established.

Lothers (1951) examined the outstanding leg part of double angle joints as beams. The study was elastic and on initial stiffness. Wales and Roscow (1983) investigated the behaviour of bolted connections under moment-axial force with series springs connected to rigid bars. Connections under monotonic bending were investigated with rigid and deformable beam elements and compared with test results. Kennedy and Hafez (1984) employed this model to study header plate joints. Similar work was done for cleated joints by Chmielowiec (1987). Driscoll (1987) analysed top-and-seat-angle combinations. De Stefano *et al*. (1994) studied double angle joints under dynamic loading, considering monotonic bending test and the slip was neglected here. Shi *et al*. (1996) modelled end plate joints with beam and yield-line theory, considering tensile, compression and shear regions. Although the model was successful in estimating the initial stiffness and yielding moments, it showed significant deviations in an ultimate moment carrying capacity since the strain-hardening effect was not taken into account.

Dynamic models were also studied with the mechanical method. Bernuzzi (1998) proposed a hysterical model for top-and-seat angle joints with EN3 (Eurocode 3) and monotonic experimental data calibration. Strain-hardening was taken into account in the model. Pucinotti (2001) worked on top-and-seat and web angle joints by revising EN3.

Studies on joints are generally made for the case of connected to the strong axis of the column. However, there are also minor combinations in reality. De Lima *et al*. (2002) proposed a new approach based on the component method for the moment-rotation relationship of semi-rigid connections that connected to the minor axis. Coelho A.M. *et al*. (2004, 2006) suggested a method to study the nonlinear behaviour of single bolted t-stub connections. Different failure modes were considered. Fracture at legs of t-stubs was considered as a beam, friction at bolts was considered with springs. End conditions were different from similar studies given in past literature. Bayo *et al*. (2006) proposed a new approach for considering the joint behaviour. In this method, finite-dimensionless four-node joint elements were used. In this approach, connections to which beams with different height are connected to were included in global structural analysis by considering their location in the structure. Urbonas and Daniunas (2006) investigated the moment-rotation curve of beam-to-beam semi-rigid connections under the effect of bending and axial force by the component method. Elastic behaviour was considered in the study. Cabrero and Bayo (2007) examined the 3D behaviour of semi-rigid joints with the component method. Minor axis combinations were also included in the study. Pucinotti (2007) suggested a new method for modelling the cyclic moment-rotation curve of top and seat and web angle joints based on the component method in the EN3 annex. J. Da Silva (2008) modelled the generalised 3D behaviour of joints (all kinds of load effects were taken as reference, that is, earthquake, fire, tsunami, hurricane etc.) based on the component method.

Lemonis and Gantes (2009) proposed a new method to obtain the moment-rotation curve of the joints based on the component method. The incorporation of the mechanical method into structural analysis is relatively complex and laborious in the procedure. To this end, Ihaddoune *et al*. (2009) proposed a new approach. In the proposed approach, joints was directly included in the structural analysis by obtaining stiffness and joint load matrices related to the serial spring and rigid bar analogy by taking the joint node in the frame as a reference. de Oliveira and de Miranda (2009) considered shear lag with stabilisation of top-and-seat angle composite joints before, and after concrete cracking. Malaga-Chiquitaype and Elghazouli (2010) examined the monotonic and hysterical moment-rotation curve of tubular column-to-open beam blind bolted angle joints.

In reality, a connection can be constructed with beams of unequal depth. Da Silva *et al*. (2012) considered this condition with the component method. Bayo *et al*. (2012) used the component method to consider the place of connections in a structure, as a cruciform element. Piluso *et al*. (2012) evaluated composite joints with a mechanical model based on the component method. This method was iterative and the iteration algorithm was presented. Abidelah *et al*. (2012) studied end plate joints under different stiffening configurations.

The component continues to be used frequently in modelling a joint characteristic. Performance of the method proved with a lot of work and it has gained some popularity modelling connection considering the real in-place situation. Besides this, the method is favourable and used frequently to study innovative and new connection types.

Wuwer *et al*. (2012) examined moment-rotation and axial force-displacement relations with lap joints in series with the spring analogy. Jordao *et al*. (2013) analysed column-beam connections under internal, external, symmetric, asymmetric and unequal beam depth conditions. A new mechanical and analytical method was proposed to model this situation by taking the component method given in EN3 as reference. Yang and Eatherton (2014) modelled phenomena such as slip at bolt and prying force with the analogy of a rigid bar-deformed spring. The modelling was done by examining the related phenomena as separate

components. Brunesi *et al*. (2014) modelled the global behaviour of joints with the analogy of shear link, rigid bar and fibre element. Skejic *et al*. (2014) studied stiffened angle cleat joints.

Shear tab joints are weak joints in terms of rigidity. This causes them to be affected by more strain components under general loads. Koduro and Driver (2014) modelled the moment-rotation curve of the joint under the interaction of moment, shear and axial force in the model proposed by considering strain components and failure modes. Latour *et al*. (2014) studied base-plates. Heinisuo *et al*. (2014) extended the mechanical method to 3D joining behaviour for the first time. Ghassemieh and Bahadori (2015) modelled cover-plate joints based on the component method. Abdalla *et al*. (2015) examined the failure of angle cleat joints by taking into account unilateral contact and friction. Loureiro *et al*. (2016) evaluated the panel zone of the joints composed with beams of different heights using 3D FEM and component method. Oosterhof and Driver (2016) mechanically examined shear connections under the column removal scenario. Bayo *et al*. (2017) made analyses considering 2D cruciform unequal depth beams (Bayo *et al*. 2017). Weigand (2017) dynamically modelled single plate joints by considering the bolt pre-tension. Alhasawi *et al*. (2017) extended end-plate joints to take into account the separation of the end-plate and the column head and the bolt group effect. Couchaux and Rodier (2017) examined end-plate joints under the influence of biaxial moment and axial force. Bayo and Gracia (2019) investigated the stiffness of welded joints in 2D, by analogy with mode shapes and metamodel and frame. In the model, the case of asymmetric beams was also considered. Hollow section joints were examined by Harada and da Silva (2019) in 3D with the component method. Latour and Rizzano (2019) analysed the moment-rotation of base-plates under a moment and axial force based on the component method. Zhu *et al*. (2019) extended the component method to post ultimate and post-fracture range. Yan *et al*. (2020) worked on the full behaviour of double web angle joints with a component based model. The model considered the load transfer mechanism, contact, plastic deformation and the load-bearing of the bolts at each stage. Loureiro *et al*. (2020) proposed a new approach for 2D welded haunched joints. Gil-Martin and Hernandez-Montes (2020) obtained a simpler and more general expression than the EN3 component method. The major change in the model was that moment and axial force can be considered together, avoiding the concept of rotational stiffness. Also, the column-panel zone was not local but was distributed over other deformation parameters of the joint. Zhao *et al*. (2020) mechanically examined brace-brace X-welded joints in X brace configurations. Reinosa *et al*. (2020) investigated the moment-rotational and axial stiffness of stiffened angle joints by mechanical methods.

### 2.4 Informational methods

Informational models are used to gain a wider range of information by making sense of various data. Most of the studies on informational models were done with neural networks using experimental data or parametric study data. The first study with informational modelling by Abdalla and Stavroulakis (1995) proposed a self-learner model using a backpropagation neural network and various data banks. In this study, many combinations was modelled with high consistency and included in structural analysis. Jadid and Fairbairn (1996) utilised an artificial neural network to investigate the relationship of behaviour and geometrical properties of joints. Stavroulakis *et al*. (1997) used a neural network for the global moment-rotation relationship of single web angle semi-rigid connections. Anderson *et al*. (1997) studied minor axis flush and plate joints. Dang and Tan (2005) suggested an inner product based dynamic model for piezoceramic actuators. De Lima *et al*. (2005) modelled moment-rotation behaviour of joints with the neural network. Yun *et al*. (2006) used the self-learning algorithm to model the looping behaviour of joints. In the model, the neural network was also included in the modelling of complex cyclic behaviour. Another study about the available rotation capacity of wide flange beams was performed by Guzelbey *et al*. (2006). Cevik (2007) used genetic programming to study rotation capacities of wide flange beams, too. Yun *et al*. (2007) modelled the hysteric behaviour of semi-rigid column-beam joints with a neural network, where self-learning simulation was also used. Pirmoz and Gholizadeh (2007) and Salajegheh *et al*. (2008) employed neural networks to estimate top-and-seat angle joints with angles.

### 2.5 Numerical method

One of the most popular methods to model moment-rotation behaviour of a connection is FEM. The reasons for this are more economic than experiments. But it is more realistic, convenient to study with a wide range of parameters and measuring local effects which are hard to include in other methods successfully (like contact force, slip at component etc.). The first study related to FEM was the work of Bose *et al*. (1972). From that date, FEM has been used many times to study the behaviour of connection.

Krishnamurthy and Graddy (1976) investigated semi-rigid joints with 3D, for the first time. Also, they reported another work correlating 2D and 3D behaviour (Krishnamurthy 1978). Eight-node sub parametric brick elements were used to study end plate connections. Bolt preloading and contact were also included and linear elastic analysis was employed but the work was expensive because of the way of including contact as attaching and releasing nodes artificially. Kukreti *et al*. (1989) worked on tee-hanger connection with hybrid 3D-2D elements. Plane elements were utilised for web and stiffeners, solid elements were used for bolts and plates. Chasten *et al*. (1992) modelled extended end plate connection with shell element. The prying force between end plate and column flange was also included in the work. Sherbourne and Bahaari (1994) simulated end plate joint under bending with 3D FEM. Brick, plate and truss elements were utilised. Gebbeken *et al*. (1994) used an eight-node brick element and took slip, in addition, strain hardening and contact problem into consideration to model end plate connection. Another model was proposed by the authors for end plate connections (Bahaari and Sherbourne 1996). Quadrilateral

shell elements and eight-node isoparametric solid elements were used in this study. Bursi and Jaspart (1998) derived 3D brick elements for T-stubs and extended end plates. A 3D elastoplastic FEM analysis model was proposed by Bose *et al*. (1997) for unstiffened flush end plate connections. In this model; weld, head of bolt and column fillets were ignored considering their low contribution to behaviour. Kukreti and Biswas (1997) studied cyclic hysteretic behaviour of end plates with 2D FEM and developed a computer program.

While many studies have been reported on joints with I profile, FEM is also important to investigate connections be formed by different cross-sections. Wheeler *et al*. (2000) investigated tubular blind bolted end plate connection with 3D brick elements. The study was verified with test results. Yang *et al*. (2000) studied double web angle joints under tensile, shear and their combinations. The work was performed with 3D elastic-plastic analysis; contact between bolt and angle and angle between column flanges was taken into account. A similar study was reported by Hong et al. (2001) and, brick elements were utilised modelling bolt, beam and angle while column modelled as spring and ignoring its tensile resistance. Citipitioglu *et al*. (2002) considered all possible contacts between components and studied the effects of bolt pre-loading and friction coefficient on double angle joints. Bahaari and Sherbourne (2000) investigated large capacity eight bolt end plate configurations with shell elements. Bolt heads and nuts were not modelled and contact between column flange and end plate was included with 3D interface elements. Sumner *et al*. (2000) investigated 4-8 bolt extended end plate connection with solid elements. Gantes and Lemonis (2003) proposed a model which can consider material and geometric nonlinearities and contacts. The model was used for t-stubs. Urbonas and Daniunas (2003) studied column-beam connections which have angles different than 90 degrees. The study was performed with 3D and it was found that angle affects the flexibility of a joint strongly. Adany and Dunai (2004) performed 3D FEM analysis for end plate joints under cyclic loads. Shell elements were used for modelling both of column-beam and column-base joints. In another study, butt-type bolted joints were investigated for 3D elasto-plastic FEM analysis by Ju *et al*. (2004). Yorgun *et al*. (2004) used brick elements for modelling double channel connections. Komuro *et al*. (2004) studied the top-and-seat-angle connection. Elasto-plastic analysis was performed and solid elements were utilised modelling elements and also, contact forces included. Abolmaali *et al*. (2005) proposed a model for flush end-plate connection, which uses eight-node solid isoparametric elements for column, beam and various components. Material, geometric and contact nonlinearities was investigated in the proposed model. Tagawa and Gurel (2005) studied steel channels as stiffeners in bolted moment connections via 3D FEM. Eight node elements were used modelling connection components. Maggi *et al*. (2005) worked on an extended end plate connection with a 3D FE model calibrated with test results. Nonlinearities, large displacements and contacts can be considered with their model. The model which can consider contact and slide between different components was proposed by Kukreti and Zhou (2006) for an eight-bolt end plate connection. Shi *et al*. (2008) proposed another model for different configurations of end plate connections and studied its behaviour under monotonic loads. In this model, 10 node tetrahedral elements were selected modelling all components of joints. Contact between column flange and end plate were considered with 3D target surface and eight-node surface to surface elements. It was reported that stiffeners have great importance on the behaviour. Diaz *et al*. (2011) improved another model to investigate extended end plate connection. Contact, preload and large displacements were considered but washers were not in order to decrease the contact surface. Mashaly *et al*. (2011) modelled contact force surface-to-surface instead of node-to-node. It was concluded that connection behaviour can be studied more realistic in this way. Wu *et al*. (2012) suggested a practical way for modelling bolts by considering their nuts and effective diameter into a shaft. Loureiro *et al*. (2012) studied minor and major axis connections and interaction between them with 3D FE. Also, non-proportional load conditions were included. Coelho (2013) modelled end plate joints with void growth mechanism and coalescence as micromechanic. The study was performed under large scale plasticity and rotational capacity was examined. Kaushik *et al*. (2014) and Ismail *et al*. (2016) studied different types of beam-to-column connection and the effect of bolt preloading and contact forces were investigated. Wang *et al*. (2013) employed eight-node linear brick elements to study the cyclic behaviour of end plate joints. The selection of an eight-node linear brick element was to avoid from the shear locking phenomenon. Besides of end plate and column flange, contact forces between bolt and end plate and other components were included.

Most studies consider in-plane bending. Despite that, Gil and Goni (2015) studied t-stubs under out-of-plane bending with a series of tests and FEM. Eight node solid elements were used and contact force considered. Nut, rod and bolt head were modelled as one part. Alhendi and Celikag (2015, 2015) studied tubular columns to open beams with reverse channel joints. Bayo *et al*. (2015) aimed joints connected beams that have different heights. In this situation, the column panel zone was trapezoidal. I beam to RHS column connections were investigated by Hadianfard and Rahnema (2010) and important stiffness reduction was observed. Also, graphics were presented for the calculation of stiffness reduction so that they can be included in structural analysis easily. Tahir *et al*. (2011) proposed a model for minor axis flush end plate joints. All components were modelled with 3D solid hexahedral elements and contact modelled as gap springs. El-Khoriby *et al*. (2017) studied joints under cyclic bending and axial forces and proposed a new model. In general, solid elements were utilised in FE studies but in this proposed model, 3D and 2D shell elements can be used rapidly with enough accuracy.

Another important area of FEM studies is composite connections. Since prior studies (Leon and Lin 1986), composite connections have been studied with a wide range. Gil and Bayo (2008) presented work for composite

connection regarding the location in a structure. For modelling, eight-node solid elements were utilised and rebars were embedded into slabs. Surface to surface contact was also included. Dabaon *et al*. (2009) studied bare steel and composite semi rigid joints for the minor and major axis. The cracking of concrete and contact was also investigated. Gil *et al*. (2013) proposed results from a set of test and FEM studies. Slab, rebar, shear studs and steel elements were modelled with eight-node solid elements. Similar to other works, rebar was embedded into slabs but contact between slab and beam flange was ignored. Second-order inelastic analysis was performed and surface to surface contact was considered both for minor and major axis end plates.

Another important area of FEM is the column-to-foundation connection, also known as base-plates. Because of the similarity between end plates and base plates, beam-to-column end plate joint studies contributed a great amount of knowledge on column base studies. Thambiratnam and Krishnamurthy (1989) employed linear elastic analysis and sub parametric quadrilateral elements to investigate base plates under the moment and axial forces. Targowski *et al*. (1993) studied square column rectangular base plates with FEM. Concrete assumed as rigid plate and thread and movement of bolts were ignored and modelled as the one-dimensional element. Kontoleon *et al*. (1999, 2000) utilised 2D FEM to study base plate regarding the thickness of base plate under the moment and axial forces. Frictional unilateral contact was regarded. Another model was proposed by Stamatopoulos and Ermopoulos (2011). Tetrahedral, brick and wedge solid elements were employed for 3D analysis. Columns were modelled with four nodes quadrilateral plate elements and anchorage rods were modelled as bar. Khodaie *et al*. (2012) proposed work on the initial stiffness of square hollow section column base plates. The soil was not modelled and displacements under the foundation were restrained. Eight node hexahedral solid isoparametric elements were used for the column, base plate and anchorage bolts. Kanvinde *et al*. (2013) modelled exposed column base with hexahedral elements. Tetrahedral elements were employed in modelling like anchor bolts and nuts where meshing was difficult. Large displacements and other nonlinearities were included. Column and base plates were simulated monolithic because they were welded. The same viewpoint was applied for anchor rods, nuts and washers. All possible surface-to-surface contact was considered but the soil was not included. Fasaee *et al*. (2018) proposed similar work under a biaxial bending moment. Razzaghi and Khoshbakht (2015) disregarded welds and modelled all elements with eight-node brick elements. All components were modelled separately, and then assembled according to joint configuration. FE studies are still in progress (Cloete and Roth 2021, Seco *et al*. 2021).

Some works should be highlighted as further studies; top-and-seat-angle bolted joint with authentic stainless steel (Hasan *et al*. 2017), skewed extended shear tab connected to web/flange (Al Hijaj and Mahamid 2017 part 1, part2); single shear plate (Suleiman *et al*. 2017, Asl *et al*. 2019), studies on joint with their location in a structure like a corner, interior, exterior, plane etc. (Diaz *et al*. 2018), I beam to hollow column blind bolted joints (Tahir *et al*. 2018), composite minor axis connection (Xu *et al*. 2019), and others (ElSabbagh *et al*. 2019, Boudia *et al*. 2020, Ma *et al*. 2020, Ma et. al. *2020*, Soares *et al*. 2021, Yan and Rasmussen 2021, Nawar *et al*. 2021).

### *2.6 Experimental studies*

Testing is very important to study semi-rigid connections. Even today, many structural design guidelines, codes and standards reference the test methods to classify or to obtain joint characteristics. On the other hand, experimental studies have lost their popularity, as the methods that are investigated thus far have verified their effectiveness with a wide range. Thus, test methods lost their place relative to prior studies. Some important reasons for this conclusion are being the most expensive than other methods, being inappropriate for practical application and being only useful for tested joint configuration. Now, experiments are used to check proposed approach accuracy or to study innovative joints. Also, they are used for suggesting a new empirical, numeric or informational model, regardless of testing first time or published data.

If test data is compiled, it can be useful for a wide range of goals. This concept is called a databank. Several data banks have been shared and can be found in the literature. Many methods, especially empirical works, are produced from the data bank and they are important information sources.

The first time a data bank was proposed by Goverdhan (1984) and has 230 tests. It contains end plate, top-and-seat-angle, double web angle, single web angle and plate, header plate. Nethercot (1985) developed another data bank which includes more than 70 experimental tests and more than 700 experiments from other researchers (Jones *et al*. 1980). Kishi and Chen (1986) collected 303 tests and generated another data bank (Kishi and Chen 1986). Then, Abdalla and Chen (1995) expanded the data bank with 46 additional test results. Another data bank called SERICON was developed by Arbed Researchers and Aachen University (Gerardy and Schleich 1991, Gerardy and Schleich 1992). Then it was extended as SERICON II by Cruz *et al*. (1998). Mak and Elkady (2021) proposed database on flush end plate connection. The study included many flush end plate configurations constructed with bare steel or composite and beam-column or beam-to-beam etc.

Some interesting experimental work should be highlighted (Li *et al*. 1996, Thomas *et al*. 2017, Beland *et al*. 2020, Hasan *et al*. 2021, Ivanyi 2000).

### *2.7 Hybrid methods*

All methods developed to date have several advantages and disadvantages. Therefore, the best method cannot be mentioned. This situation paved the way for the idea of using the methods in a hybrid way to maximise the advantages. Foley and Vinnakota (1995) used empirical-analytical methods together. Pirmoz *et al*. (2009) established the relationship of top-seat angle joints under

moment-tensile interaction semi-analytically (Pirmoz and Danesh 2009). The method was supported by FE analyses. Kim *et al*. (2012) combined the mechanical and informational models.

Abdollahzadeh *et al*. (2014) used the mechanical method and neural network structure together for the hysterical behaviour of end plate joints. Also, Abdollahzadeh *et al*. (2014) studied column base plates with the same approach. Fernandez-Ceniceros *et al*. (2015, 2015) combined numerical and informational methods.

Omer *et al*. (2018) proposed a new hybrid method within the framework of 3D numerical analysis. The method was analytical and based on 2 parameters. The necessary parameters for plotting the moment-rotation curve were the initial stiffness and the maximum moment capacity, and the initial stiffness was calculated by the component method, while the moment was calculated empirically over the initial semi-rigidity.

Kueh (2021) established the moment-rotation relationship with neural network and multi-linear regression analyses for flush end plate joints.

### 2.8 Moment-axial force and/or shear interaction

Joints are not only affected by the moment. Especially under horizontal forces, the axial force is observed in column-beam joints. In addition, the axial force is at an important level in the joints of the vertical structural elements. In this case, the joint components will not be under the influence of only one load, and a structure response will be observed under the interaction of these forces. In this regard, the axial force-moment interaction is important. Da Silva *et al*. (2001) studied the behaviour of semi-rigid connections under bending-axial force interaction. As a result of the study, it was observed that the presence of axial compressive force significantly reduced the stiffness of the joint.

Del Savio *et al*. (2009) proposed a method based on the component method to obtain the moment-rotation relationship of column-beam connections under moment-axial force interaction. Pirmoz *et al*. (2011) investigated the moment-rotation curves of top-and-seat-angle joints with 3D FEM under axial force-moment interaction. Since the presence of axial force significantly affects the moment-rotation curve, a method has been presented to arrange the existing curves under the presence of axial force.

Abou-Zidan and Liu (2015) examined shear tab connections. In addition to the shear effect, horizontal buckling was also taken into account. Chenaghlou M.R. and Nooshin (2015) obtained the moment-rotation relationship under the moment-axial force interaction in the base plates.

Goudrarzi *et al*. (2017) tested flush-end-plate joints with monotonic and cyclic loading under various axial loads. It was observed that axial compression increases initial stiffness, yield moment, and energy dissipation while axial tension decreases them. El-Khoriby *et al*. (2017), working within the scope of FE parametric analysis, reported different results on the combination of cyclic bending and axial compression force. The presence of axial compression significantly reduces the bearing capacity of the joints, especially the end plate and header plate joints.

Daneshvar and Driver (2018) examined the moment-axial force-shear interaction of single angle joints under the column removal scenario. Motallebi *et al*. (2018) investigated stiffened extended shear tab joints with FEM under gravity induced shear forces.

### 2.9 Axial force-axial displacement

Although wide-ranging research has been done on the moment-rotation relations of the joints, the number of studies dealing with the force-displacement relations in the direction of other freedoms is limited. The most important of these relationships is the axial force-displacement relationship. De Stefano and Astaneh (1991) examined this relationship for double angle connections. In the study, two methods, analytical and empirical, are proposed for the axial force-displacement relationship.

Prying force becomes important in thin flange-wide bolt t-stub joints. For a more effective approach, Yang *et al*. (2013) proposed an analytical model. Reinosa *et al*. (2013) used the frame analogy for the axial stiffness of t-stubs. Francavilla *et al*. (2015) examined finite element and t-stub joints. Reinosa *et al*. (2015, 2015) extended the frame analogy to stiffened and unstiffened angle cleats.

### 2.10 Shear-Vertical displacement

It is not possible to talk about only the moment-rotation relationship in the joints. Many joints that are considered pin-joint transmit a certain amount of moment. However, the dominant feature about rotation in such joints is not the moment but the shear force (Astaneh 1989). Astaneh A. (1989) proposed standardised shear-end rotation relationship for simple beams. According to the study, the elastic limit was reached when the midspan bending moment equals yielding moment. Beyond this point, the curve was non-linear. Even under a small amount of shear increase, a large increase was seen at the end rotation. Beside this, there is a relationship between shear force and vertical displacement. Some information was given in literature. Nader and Astaneh (1996) studied one bay-single story frames with shaking table tests. It was reported that the stiffness of semi-rigid joints was not stable as a rigid joint due to bolt slip and bolt hole enlargement under cyclic loading. Astaneh *et al*. (1993) studied single plate shear connection with different bolt configurations. It was concluded that joints were sufficiently ductile to tolerate maximum shear. Similar work can be found in literature; however, studies on shear force-vertical displacement/rotation are limited relative to the moment-rotation relationship. Studies in the literature were related to ductility requirements and design aspects, rather than relationships.

### 2.11 Torsion

For the joints to be modelled exactly, torsion must also be taken into account. Phenomena such as lateral buckling, torsion and wrapping cannot be fully studied unless torsion

is taken into account, and this is of great importance not only for the joint but also for the beam. In practice, joints against torsion are considered rigid. Gil *et al*. (2015, 2019, 2020) carried out many studies on the subject. As a result of the experiments and numerical analysis, it was seen that the joints were semi-rigid in terms of torsion. The asymmetric t-stub analogy was used to model the torsion-rotational relationship of the connections with the component method. Although torsion is one of the most important and well studied topics in steel design, the torsion relationship of steel connections is not well documented. Studies generally focus on design requirements.

## 3. Analysis of semi-rigid frames

Defining the moment-rotation relationship alone is not sufficient for the analysis of semi-rigid connections. To perform structural analysis, the relevant boundary conditions need to be arranged. While the first studies on the subject were on the slope-deflection method, it accelerated with the development of matrix methods and electronic calculators. Lightfoot and Baker (1961) arranged the slope-deflection method in the form of a matrix and suggested correction matrices to include the joint stiffness into account. Monforton and Wu (1963) carried out the first work on the analysis of semi-rigid frames by matrix methods. The general element stiffness matrices were arranged according to the semi-rigidity.

The first work on the dynamic analysis of semi-rigid frames was done by Lionberger and Weaver (1969). Dynamic analysis was done with matrix formulations of column-beam elements resting on elasto-plastic rotational springs. The authors suggested that the curve should be considered bi-linear since the non-linear characteristic of a connection is difficult to calculate. Razzaq (1983) modelled the moment-rotation relationship piece-wise in the investigation of the end constraints effects on the strength of the columns. Razzaq and Calash (1985) modelled the relationship obtained by the mechanical method as tri-linear to model semi-rigid connections in column buckling. Yu and Shanmugam (1986) suggested using the stiffness constant in the arrangement of stiffness matrices of the semi-rigid connections. Sivakumaran K.S. (1988) modelled the cyclic characteristic of the joint as bi-linear in the dynamic analysis of semi-rigid connections. Poggi (1988) worked on the joint directly as a beam element, not as a separate element. Thus, the joint eccentricity was also taken into account. The beam element was made by adding a rigid bar to its ends to represent the joint eccentricity and a rotational spring to represent the rotation of the joint. In dynamic analyses, the moment-rotation relationship was considered as a piece-wise model.

Yu and Shanmugam (1988) examined the stability of semi-rigid space frames by arranging stiffness matrices with a fixity factor. Al-Bermani and Kitipornchai (1992) proposed matrix formulation for elasto-plastic non-linear analysis of 3D semi-rigid frames. In-plane, out-of-plane and torsion were also considered in the method. Yau and Chan (1994) modelled the joints and material nonlinearities as springs in series with the beam element for non-linear analysis of semi-rigid frames.

Defining a rotational spring is not an obligation to include the joint characteristics in the structural analysis. Li *et al*. (1995) proposed a connection element to include the moment-rotation relationship of the joint and its eccentricity to the element axes in 3D frame analysis. In this method, both flexibility and eccentricity can be modelled by representing the moment-rotation relationship of the joint as beam element.

Gao and Haldar (1995) proposed a model for hysterical damping of the joint for dynamic analysis of semi-rigid frames. Bhatti and Hingtgen (1995) suggested taking the stiffness as zero in the second segment of the curve in the bi-linear joint model for a conservative design in unbraced semi-rigid frames. Khudada and Geschwindner (1997) proposed a method for incorporating geometric and material nonlinearities into dynamic analysis of semi-rigid steel frames, using the mode superposition method. In the proposed method, both the joint and the panel zone were obtained by adding two rigid bars to the spring and arranging the corresponding matrices by mechanical modelling of the panel zone.

Line combinations are generally used when idealising the moment-rotation curve of the joint. In contrast, Ahmed and Nethercot (1997) used a line for the linear part and an elliptical spring for the nonlinear part in the moment-rotation curve for idealisation of composite flush end plate connections. Vellasco *et al*. (2006) performed a parametric analysis on portal frames with steel and composite semi-rigid joints. In the study, a new method was proposed to be applied in cases where rotational springs cannot be modelled. In the method, while the beams were considered hinged, the spring was not at the end of the element but was connected from a distance between the elements as far as the joint distance. Liu *et al*. (2008) developed an element to corporate joint flexibility and plastic hinge. To do this, semi-rigid joints and plastic hinges were modelled in a series of springs, called a compound element. Lee and Han (2011) proposed an element in which the plastic hinge and joint flexibility can be modelled together. The rotational limit of the joint was also included in the analysis in this element. Nguyen and Kim (2014) presented a new approach for non-linear time history dynamic analysis, in which non-linear damping of the joint was also considered. Saritas and Koseoglu (2015) proposed a quadrilinear model for the dynamic moment-rotation curve.

The moment-rotation relationship with the plastic hinge has always been made with the local plastic hinge definition until now. Nguyen and Kim (2015) modelled distributed plasticity together with the moment-rotation relationship. Koriga *et al*. (2019) proposed a formulation that can be modelled in semi-rigid frames without the need for FE meshing.

## 4. Design methods for semi-rigid frames

Designing semi-rigid frames differs from traditional frame design approaches. The flexibility of a semi-rigid joint contributes to the nonlinearities of a structure. Besides this, to analyse statically indeterminate structures, pre-

design must be done in practice. The pre-design process is done for the structural system but how to incorporate joint stiffness is unclear. Thus, iteration between frame design and joint design is nearly unavoidable for traditional frame design algorithms. The design process can be seen as troublesome for practical application. Additionally, using a semi-rigid connection may be seen as impractical. Until this time, some works have been reported to eradicate the iteration process. A little attention has been given to different design philosophies.

The first idea was given with the starting studies. It was based on intersecting a beam-line and the moment-rotation behaviour of a connection. Beam-line is a line drawn by a fully rigid support moment and rotation for pinned (Jones *et al*. 1983). Johnston and Hetchman (1940) suggested a method for using the flexibility of joints at simply supported beams. The proposed method was valid for linear-elastic analysis and the authors suggested using joints under the elastic limit for safety. Springfield (1987) suggested taking joint stiffness as structural variables in pre-design, as a design parameter. Lui and Chen (1988) used braces compensating for stiffness degradation in a semi-rigid frame. In this way, not only the nonlinearity but also the requirement for iteration was eliminated. Gerstle and Ackroyd (1990) studied semi-rigid frames with the perspective of AISC (American Institute of Steel Construction) specification (AISC 360-16 2016). It was concluded that a semi-rigid frame should be analysed under allowable stress design using initial stiffness, while it should be analysed load and resistance factor design using the full nonlinear curve. Mohammed and Simitses (1990) showed that linear analysis is sufficient in stability analysis if the moment on the joint is not relatively high. Xu and Grierson (1993) developed a new design method based on continuous-discrete optimization. The method was applied successfully to decrease iteration steps. Kishi *et al*. (1993) suggested a computer program that integrated connection data banks to design frames. Mourad *et al*. (1995) designed a connection to carry 1.3 times greater than beam plastic capacity. In this way, a connection was loaded less than its 73 percent of capacity and it decreased the iteration process caused by stiffness degradation. Also, it was concluded that linear elastic analysis can be performed if a connection is designed to satisfy this conclusion. To make practical the designing semi-rigid frames, Morris *et al*. (1995) emphasised the importance of the empirical method as a useful tool and suggested expanding codes and standards to include semi-rigid frames. Also, it was suggested that charts, diagrams and menus can be useful, too. Dhillon and O'Malley (1999) developed an interactive and iterative design method for semi-rigid frames. Also, a pre-design approach was suggested to decrease iteration numbers. Rex and Goverdhan (2000) suggested another iterative design method for semi-rigid buildings with separating the design stages. Degertekin and Hayalioglu (2004) took joint stiffness as a design parameter and included it in the design process. Cabrero and Bayo (2005) proposed a method to design semi-rigid structures with minimising the iteration. According to the proposed method, some parameters like joint stiffness, resistance and ductility were pre-designed. Then, the traditional frame design algorithm was performed. The method was given with elastic and plastic design approaches. Rizzano (2006) proposed another method based on taking stiffness as a design variable. According to this method, a stiffness value should be selected for structural analysis. After the frame design was completed, the joint can be designed appropriately to select stiffness. Popa *et al*. (2010, 2011) investigated semi-rigid connection with performance-based design criteria. Xu and Ellingwood (2011) processed progressive collapse analysis of semi-rigid frames. The idea of using semi-rigid and rigid frames together was suggested several times by different authors (Abolmaali *et al*. 2012, Reyes-Salazar *et al*. 2014, Bayat and Zahrai 2017). Stamatopoulos (2012) included column flexibilities into the frame design. Then, another study was performed to suggest an iterative design algorithm of column flexibilities by the author (Stamatopoulos 2015). Singh and Lui (2014) employed the beam-line approach to reduce iteration steps and to find optimal connection configuration. D'allesandro *et al*. (2018) tabulated the component method for more practical use.

## 5. Conclusions

Since the first test carried out in the early 20th century on semi-rigid connection, many works have been proposed and very important contributions to the literature to understand the behaviour. With these efforts, connection behaviour could be modelled more realistically. One of the important conclusions of the studies is connection classification systems (Bjorhovde *et al*. 1990, Hasan *et al*. 1998, Goto and Miyashita 1998, Nethercot *et al*. 1998, Jaspart *et al*. 2008). However, using semi-rigid connections can be still seen as impractical, even considering the great effort given to the subject. Authors reviewed a wide range of documents shared from the 1900s to nowadays and based on this; several valuable criticisms have been made. These are given below; hoping to contribute to future studies and, wishes these considerations to mediate semi-rigid connections to find more place in practice.

- According to the code based design or connection classification system, a structure can be determined as semi-rigid, continuous, partial strength etc. This classification is about how to analyse a structure. And, in reality, many connections still behave differently. Even if it is assumed to be perfectly rigid or pinned, a connection probably shows some flexibility or transfers some bending moment. These assumptions are still two unrealistic extreme cases. Despite this, a structure can be designed more realistic, maybe economically, taking into account its flexibility even if it's classified as rigid or pinned.
- Today, many design codes or standards cover a very limited design philosophy. Concepts like special moment frame, intermediate braced frame which is for the seismic application don't consider the pure nature of a connection. The frame is considered rigid/fully strength or hinged. Parallel to this, works on design philosophies of semi-rigid/partial strength frames are limited. To obtain more economic and safe design, semi-rigid design approaches

Table 1 Comparison of modelling methods of semi-rigid joints

| Methods | Cost of Process | Being Easily applicable | Feasibility to different joint configurations | Proximity real behaviour |
|---|---|---|---|---|
| Analytic | Low | Medium | Low | Low |
| Empiric | Low | High | Low | Low |
| Mechanic | Medium-high | Medium | High | Medium-high |
| Informational | High | Low | Medium | medium |
| Numeric | High | Low | Very high | High |
| Experiment | Very high | Low-medium | Very low | Very high |
| Hybrid | Medium-high | Very low | Medium | Medium-high |

should be more included in both design guidelines and research studies.

- It is not possible to talk about the best methods for the methods developed so far (see Table 1). Each method has its advantages and disadvantages. This complicates the application in practice. For an ordinary designer, clear boundaries are not drawn on which method can be preferred, how much a method can be relied on and how much it can be applied to what kind of scope. Therefore, it should be determined which method can be used safely under its boundaries. Knowing this will make a great contribution not only to semi-rigid designs but also to rigid and pinned designs.
- Connection details given in code and standards may not be preferred for today's applications. For this case, many guidelines referred to experimental testing to determine the class of a connection as rigid or hinged. Yet, the numerical method is a powerful tool for this purpose. For the everyday challenge, the numerical method should be highlighted for the place of experiments as an expensive method.
- The authors determined over 1500 publications as thesis, article, book, report, conference paper etc. about the subject. Depending on the available documents and knowledge, the idea of semi-rigid construction separated from other steel structures as a construction method appears. Beyond frame structure, studies on various construction techniques like composite, truss, space structure have gained popularity. Thus, the semi-rigid connection can be considered as a different construction technique within design guidelines, handbooks and other helpful tools.
- Every method has its advantages and disadvantages as stated before. The solution to this may be hybrid methods. If the studies on hybrid methods increase, significant developments can be seen.
- Besides determining the characteristics of the joint such as moment-rotation, a big problem occurs: how to design it. The approaches given in the literature on this subject are summarised in section 4. The main problem here is that the practical applications can be very wide and difficult to detect. It should be considered that each developed method has its advantages and disadvantages. As an ideal solution for practical applications soon, it is suggested by the authors to prepare joint catalogues by an authority (institute, university, professional chamber, professional office, commercial firm) and create a database with hybrid methods.
- Although the concept of semi-rigidity is generally associated with moment-rotation studies have shown that this is also true for other freedoms. In this regard, the greatest gap is seen in the case of shear and torsion. Similarly, although the majority of the studies in the literature consist of I profiles connected to the strong axis of the column, this situation is a little shallow for practical applications. In addition, studies have mostly been performed for the column-beam connections, and other connections in a steel structure can be used in a wide range of ways and have the same importance. More research should be done on load-displacement relations, out-of-plane behaviours, minor-major axis interaction, moment-axial force/shear interaction in different profiles, different degrees of freedom, especially in the other structural systems.

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