Classification system for aluminium alloy connections

CLASSIFICATION SYSTEM FOR ALUMINIUM ALLOY CONNECTIONS

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Summary

The main problems related to the classification of structural joints in metal structures are discussed in this paper. A new, more general approach, specifically conceived for aluminium alloy structures, is presented in order to overcome the typical limits of existing classification systems, mainly concerned with beam-to-column steel joints. It allows for all load cases to be taken into account. The system is based on a new concept of characteristic length, which allows for a direct comparison between the connection and the connected member.

1. Introduction

In the field of codification of aluminium alloy structures the need for a new assessment of the calculation methods for connections is felt, in order to take into account the actual mechanical feature of these materials. As well known, aluminium alloys exhibit a σ–ε relationship of round-house type, which can not be interpreted through the classic elastic-perfectly plastic idealisation, commonly adopted for steel, also becouse the inelastic extension of some alloys is prematurely limited by low values of ultimate strain. In addition, the behaviour of aluminium alloy structures strongly depends on the chemical composition of the material, the fabrication process, as well as on the heat treatment and presence of reduced strength zones due to welding. Looking forward to a future assessment of appropriate procedures for the evaluation of mechanical features of joints (see for example methods for the evaluation of M versus φ relationship), a preliminary stage is necessary, consisting of a new classification system for connections. This represents a basic tool to establish whether a given joint must be specifically considered into the global analysis of a structure or can be ignored, depending on its mechanical features. In fact, according to the recent knowledge, a joint may be also considered as a sort of "structural imperfection" [1], making the structure under consideration different with respect to the ideal fully rigid or fully pinned scheme. For this reason, it is of prime importance to determine to what extent the disturbance introduced by the joint may be disregarded in the structural analysis and, on the contrary, in what cases it has to be suitably taken into account with appropriate behavioural models. This aspect has being also discussed within the activity of the CEN-TC250/SC9 Committee chaired by Prof. F.M. Mazzolani, which is working out the first edition of Eurocode 9 "Aluminium Alloy Structures" [2]. A general agreement on the opportunity to improve existing approaches to the classification of connections has been reached by all countries.

2. General Requirements for a Classification System

In spite of its importance, in the field of structural analysis, the problem of predicting the actual behaviour of joints is not yet thoroughly solved. In practice, in order to perform an accurate analysis of the structure, the main objective would be that to establish an useful criterion to classify connections as pinned or rigid, in such a way their existence may be disregarded in the calculation of the structure. Nevertheless, it is well known that the actual response of many joints may be neither perfectly pinned nor rigid and that the joint semi-rigidity strongly influences the structural behaviour of the whole system, affecting the overall deformability as well as the load carrying capacity. In these cases, a proper design of the structure should be therefore based on the actual load versus displacement characteristic of the joints. The structural system should be consequently considered as semi-continuous, taking account for the structural properties of connections in terms of strength, stiffness and deformation capacity.

The analysis of a structure should be performed by following the three fundamental steps:

- Classification of connections by checking their properties in terms of stiffness (rigid , semirigid, pinned), strength (full strength or partial strength) and deformation capacity (ductile, semi-ductile, brittle);
- Representation of the load-displacement curve of the joint in a suitable analytical form (this step is skipped in the case of fully restoring joints);
- Modelling and analysis of the structure.

The aim of a classification system is just to define appropriate behavioural classes as a function of the properties of the connected members. This turns to be important also at the light of the method adopted for structural analysis. The assumption made in the global analysis of the structure shall in fact be consistent with the actual behaviour of the joints. For example, in case of linear elastic analysis the classification must be essentially referred to initial rigidity only and a semirigid connection can be modelled by a simple elastic spring, whose elastic constant represents the connection stiffness. Similarly, in the application of plastic design, relying on the assumption of rigid-plastic behaviour of the joints, the connections must be mainly classified referring to strength (see Section 5). Particular cautions should be adopted when a reduced joint deformation capacity is available. In this case, full strength connections should be provided with an extra reserve of resistance in order to cover possible overstrength effects in the members. On the contrary, if the connection has a design resistance less than the connected member one, a sufficient deformation capacity is always required in order to allow for the plastic mechanism to be developed.

Apart from the above considerations, at the light of practical applications, a quantitative criterion as basis of the joint classification is needed. It must provide the boundaries of the behavioural ranges as well as adequate criteria for comparing the connection properties with those of connected members.

3. Consideration on Existing Classification Systems

In the field of steel structures, different joint classification systems have been proposed in technical literature referring to moment resisting frames [3]. It should be pointed out that the term "joint" is generally defined as the part of the structure which transfers the internal forces from one member to another one, including the connection itself, represented by the mechanical fastening system, and the interaction zone between members.

According to EC3 [4], the beam-to-column joints are classified as pinned, semirigid or rigid, depending on the ratio of the connection initial rotational stiffness to the bending stiffness of the connected member. By assuming the whole length of the connected beam as the relevant parameter for the evaluation of member stiffness, the following boundary limits are defined:

- nominally pinned for $\bar{k} \leq 0.5$
- semirigid for $0.5 < \bar{k} < \bar{k}^*$
- rigid for $\bar{k} \geq \bar{k}^*$

where $\bar{k}$ is a non-dimensional stiffness parameter given by $\bar{k} = k_i L / EI_b$, k_i being the initial rotational stiffness of the connection and I_b, L the moment of inertia and the length of the connected beam, respectively. The value of the parameter $\bar{k}^*$ is equal to 8 or 25 for braced and unbraced frames, respectively. These values have been fitted in such a way that the critical elastic multiplier of the vertical loads does not reduce more than 5% when the actual joint rigidity is considered instead of a fully rigid behaviour. This means that only when the effect of joint actual stiffness is negligible on the frame global response, EC3 provision allows for the joint existence to be disregarded in the frame analysis.

With reference to the flexural resistance, the beam-to-column connections are classified as:

- nominally pinned for $\bar{m} \leq 0.25$
- partial strength for $0.25 < \bar{m} < 1$
- full strength for $\bar{m} \geq 1$

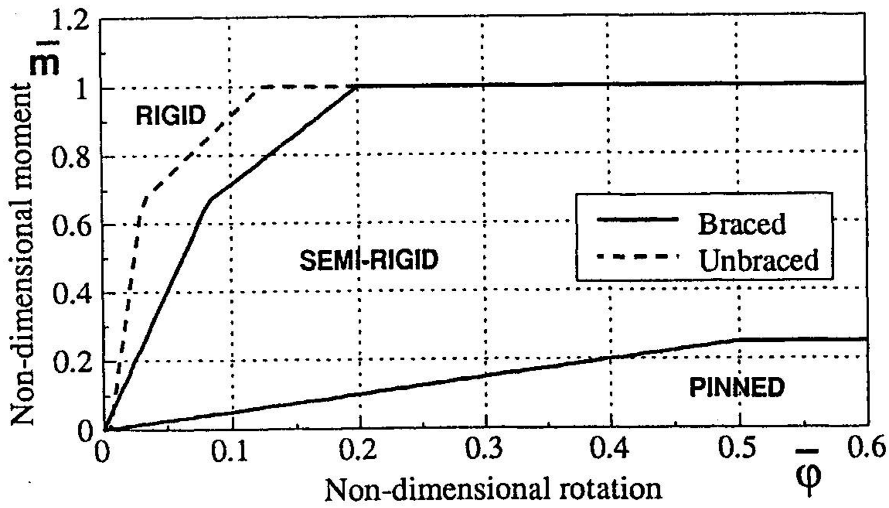

Fig. 1. Connection classification according to Eurocode 3.

$\overline{m}$ being a non-dimensional strength parameter given by $\overline{m} = M_u / M_{pb}$, in which M_u is the peak value of the design moment versus rotation curve of the connection and M_{pb} is the plastic resistance moment of the connected beam. In addition, the control of rotation capacity is not necessary for full strength connections having $\overline{m} \geq 1.2$.

The range of semirigid and rigid connections are bounded by means of a three-linear curve in the ($\overline{m},\overline{\varphi}$) plane, where the non-dimensional rotation is defined as $\overline{\varphi} = \varphi\left(EI_b / M_{pb}L\right)$. The first branch stands up to the value $\overline{m} = 2/3$ for both braced and unbraced frames, whereas the horizontal one starts from a value of $\overline{\varphi} = 0.12$ for unbraced frames and of $\overline{\varphi} = 0.20$ for braced frames (Fig. 1). The boundary curve between semirigid and pinned connections is defined by means of a bi-linear curve. For both braced and unbraced frames, the second branch, which corresponds to the horizontal plateau, starts from the values $\overline{m} = 0.25$ and $\overline{\varphi} = 0.50$ (Fig. 1).

The EC3 classification is based upon the effect of connection on the global response of the frame and is dependent on the length of the connected beam. A different method of classification, which allows to compare directly the connection rotation and the beam curvature, has been proposed by Bjorhovde, Colson and Brozzetti [5]. Such a method is based on the concept of equivalent reference length, assumed as the length L_e of the connected beam whose flexural stiffness EI_b/L_e is equal to the initial rotational stiffness of the connection. On the base of experimental data, the limits of connection stiffness, for both braced and unbraced frames, have been fixed equal to L_e=*2d* and L_e=*10d* (*d* is the depth of the beam) in case of rigid-to-semirigid and semirigid-to-flexible connections, respectively. With regard to the ultimate strength, the Authors suggest moment values of 0,7 M_p and 0,2 M_p for rigid-to-semirigid and semirigid-to-flexible limits, respectively.

Other classification systems, which are independent of the beam length, have been proposed in [6] and [7]. Bijlaard and Steenhuis [6] propose a method based on the same approach of EC3, but with a constant ratio between length and depth of the connected beam (*L*/*d*=25 for unbraced and *L*/*d*=20 for braced frames). In the same way, Tschemmernegg and Huter [7] suggest a classification system in which the distinction between braced and unbraced system is

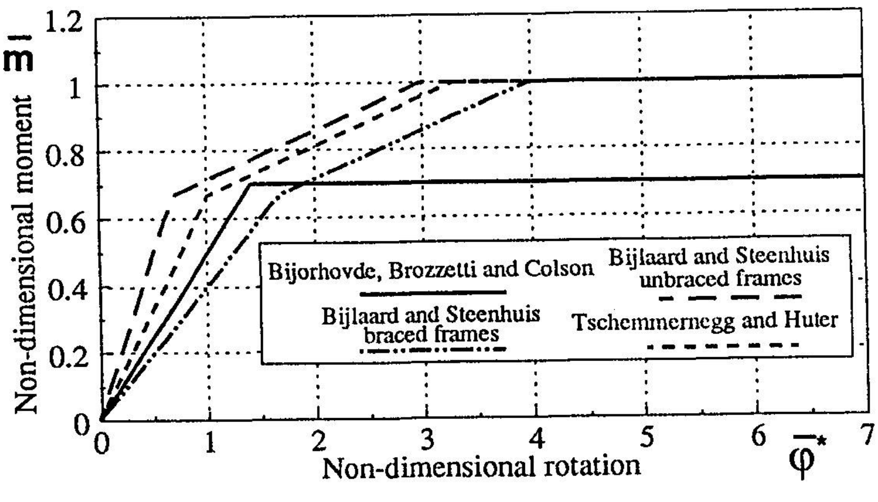

Fig. 2. Boundary curves for different classification systems.

eliminated. In this case the *L/d* ratio is assumed to vary in such a way to comply with the EC3 joint behavioural limits. A comparison among the above mentioned approaches is depicted in Fig. 2. In this case the non-dimensional rotation parameter has been assumed as $\bar{\varphi}^* = \varphi\left(EI_b / M_{pb}d\right)$.

4. Needs for a Wider Generality

All the classification systems referred to in the previous paragraph, as well as that proposed in EC3, are mainly concerned with beam-to-column connections. In addition, they account for initial stiffness and ultimate strength separately, without considering the problem of ductility and without taking into account the global behaviour of the connection. For this reason, the existing criteria classify the connections with regard to rigidity or strength independently of each other. Besides, they mostly apply to moment resisting frames, where the moment versus curvature relationship represents indeed the most relevant parameter of the structural behaviour, in particular as far as the global structural response in terms of stability and strength is concerned. This appears as a logical consequence of the wide use of steel moment resisting frames in the current practice. Nevertheless, a need for a more comprehensive approach to the classification of connections is felt, in order to cover also the remaining load cases, namely axial load and shear. This generalisation turns to be particularly suitable in the field of aluminium alloy structures. In fact, in this case, moment resisting frames seldom occur in practice, whereas trussed structures, whose members predominantly work in axial load, can be more frequently used.

On the other hand, some important differences between steel and aluminium alloys also stand from the mechanical point of view, the post-elastic behaviour of aluminium alloys being characterised by peculiar aspects, such as the strain hardening of the material and the available ductility. These aspects can not be ignored in the evaluation of ultimate load bearing capacity of the structure [8], because the strain hardening can produce some unexpected overstrength, whereas the reduced ductility can result in a limitation to the full development of the predicted collapse mechanism. In addition, it is to be considered that the behaviour of aluminium alloy structures is deeply affected by the chemical composition of the material, the fabrication process (extrusion and successive straightening), heat treatment and presence of reduced strength zones due to welding. As a consequence, the analytical computation of the joint response strongly suffers this drastic increment in the number of variables, also by considering the possibility to combine different aluminium alloys for each joint basic component.

This is the main reason why a proposal for a more general classification system is presented in this paper. For this purpose the definitions of generalised force and generalised displacement are introduced, so to cover also cases different from the common moment-rotation relationship. These two parameters account for any possible load-deformation combination. At the same time, a different concept of characteristic length is set up in order to simplify the classification of joint behaviour with respect to the connected member properties. This approach has been shared also within the EC9 Committee, which introduced the classification proposed herein into the chapter 6.4 "Classification of Aluminium Alloy Connections" of the first edition of EC9 [2].

5. A Proposal for a Classification System for Aluminium Alloy Connections

The classification system proposed herein is basically concerned with connections instead of joints. It has been conceived in such a way to achieve a wider generality with regard to the internal actions accounted for as well as the evaluation of joint mechanical features. In fact, this classification applies to all connection typologies subjected to whichever load condition. This has been thought in order to overcome the conventional classification systems for steel connections, which are strictly related to beam-to-column joints, subjected to bending moment. In addition, all mechanical features, namely initial stiffness, ultimate strength and deformation capacity, are involved all at once in the assessment of joint behaviour.

The joint is basically classified according to its capability to restore each one of above properties referred to the connected member. In this way the joint is considered as a sort of imperfection, which must be taken into account in the global structural analysis when it is not able to guarantee the same structural features of the members it connects. This can be considered as an application of the concept of the "industrial frame" according to which also the semirigid behaviour of the joint is interpreted as a "structural imperfection" [1]. The criterion under consideration is based only on the ratio of the properties of the connected

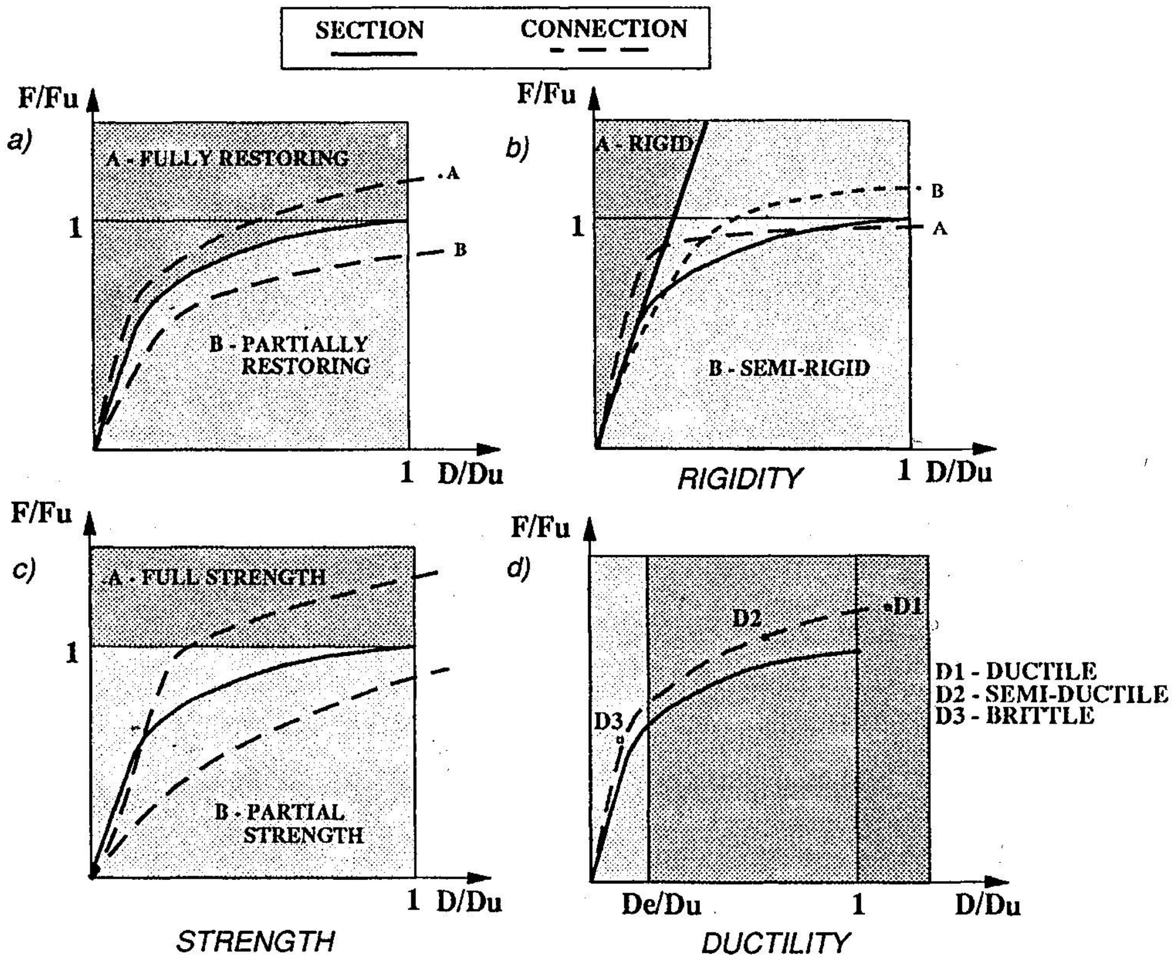

Fig. 3. Connection behavioural classes.

member to those of the connection. Therefore, it is independent of the overall structural response and in particular of the length of the connected members. At the same time, no distinction is made between braced and unbraced frames.

As being stated, the connections may be divided into two fundamental classes (Fig. 3a):

- Fully restoring connections;
- Partially restoring connections.

The former are designed in such a way to have all behavioural properties not lower than those of the weakest connected members. In this case, the existence of the connection may be ignored, regardless of the method of global analysis adopted.

In addition, the restoring features of the connection can be also referred singularly to:

- Elastic rigidity;
- Ultimate strength;
- Ductility.

In this way, it is possible to have connections the following types of connections:

- Rigid and semi-rigid depending on the ratio of their elastic stiffness to that of the connected member (Fig. 3b);
- Full strength or partial strength with reference to the member ultimate strength (Fig. 3c);
- Ductile or non-ductile (semi-ductile or brittle) with reference to member ultimate deformation capability (Fig. 3d).

In order to achieve a more generality, in the above figures the parameters of generalised force (F) and displacement (D) have been considered, expressed in non-dimensional form by means of the ultimate generalised force (F_u) and generalised ultimate (D_u) and/or elastic (D_e) generalised displacement of the connected member section.

In partially restoring connections the behavioural properties of the connection do not reach those of the weakest connected member at least with regard to one property (rigidity, strength or ductility). As a consequence of this, specific allowance for connections should be made depending on the type of global structural analysis. The general requirements for each type of analysis are summarised in Tab. 1. As a general rule, the execution of an elastic analysis requires the connection semirigidity to be taken into account. In the same way, in plastic global analysis, ultimate strength and/or ductility must be accounted for as possible weakening sources for the structures. As far as deformation capability is concerned, when partial strength, ductile connections are involved, the elongation or rotation limits of the connection may be ignored in structural analysis. In partial strength, semi-ductile connections, in which the ductility is lower than the connected member one, elongation or rotation limitations must be considered in inelastic analysis. Brittle connections, which have a ductility lower than the elastic limit deformation of the connected member, must be considered in any kind of global analysis by means of an appropriate check.

All the above considerations lead to the conclusion that the restoring properties of a connection are to be defined in such a way that the connection does not represent a weak point within the structure. Therefore, the existence of the connection must be considered in the structural analysis, depending on the property which is not restored.

6 Definition of Characteristic Length

A direct comparison between the generalised deformation of connection and that of the connected member is required for defining the connection restoring capacity in terms of rigidity and ductility. For this reason, it may be convenient to resume the concept of equivalent reference length, already introduced in [5]. In the present proposal, this can be more effectively defined as characteristic length and corresponds to the length of the member section to be considered in the comparison between connection and connected member. The characteristic length L_c can be therefore intended as the part of member which, starting from an ideal continuous structure, is substituted by the insertion of the connection. It is a function of the joint typology as well as of the connection geometry and it is essentially composed of three different parts:

- The connection itself;
- The member section L_b affected by deformation due to concentrated actions;
- The ideal intersection zone in the joint among connected members, if present.

The latter is often represented by the panel zone, which is common in beam-to-column joints. As far as the length L_b is concerned, it can not be determined "a priori", being dependent on

Method of global analysis	*Type of connection which must be accounted for*	*Type of connection which may be ignored*
ELASTIC (Linear or Non-linear).	Semi-rigid connections (Full or Partial strength, Ductile or Non-ductile) with or without restoring of member elastic strength; Partial strength connections (Rigid or Semi-rigid, Ductile or Non-ductile) without restoring of member elastic strength.	Fully restoring connections; Rigid connections (Full or Partial strength, Ductile or Non-ductile) with restoring of member elastic strength; Partial strength connections (Rigid, Ductile or Non-ductile) with restoring of member elastic strength.
PLASTIC (Rigid-plastic, Elastic-plastic, Inelastic-plastic).	Partial strength connections (Rigid or Semi-rigid, Ductile or Non-ductile) without restoring of member elastic strength.	Fully restoring connections; Partial strength, Ductile connections (Rigid or Non-ductile) with restoring of member elastic strength; Full strength connections.
HARDENING Rigid-hardening, Elastic-hardening, Generically inelastic)	Partially restoring connections	Fully restoring connections

Tab. 1. General design requirements.

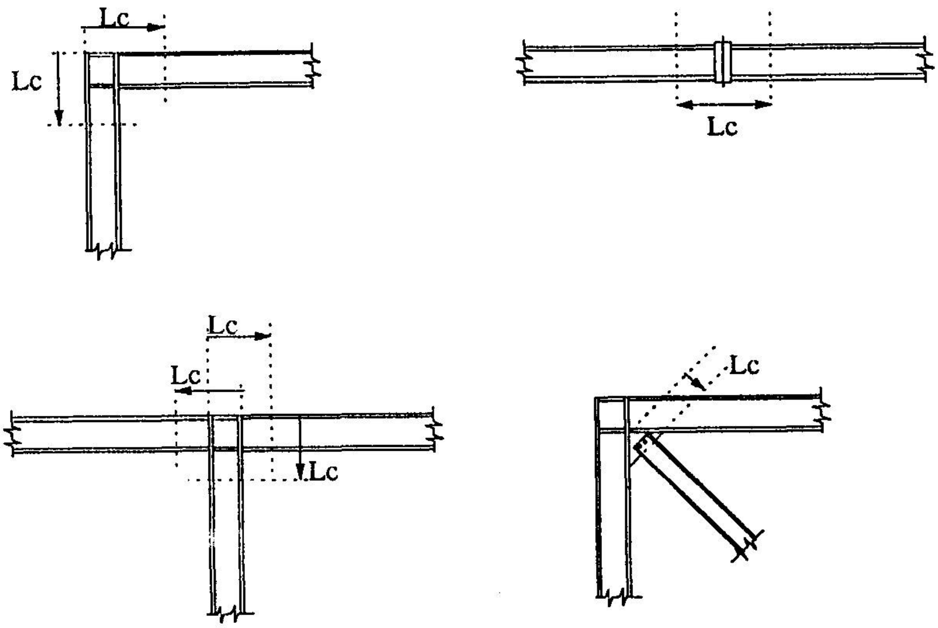

Fig. 4. Characteristic length definition.

both the existing internal action and the deformation mechanism of the joint. In a simplified way, it may be approximately assumed equal to the depth of the member for bending and shear actions and equal to zero for axial actions, unless more reliable evidences do not confirm that more limited or extended member zones are involved in the joint deformation mechanism.

The comparison between the connection and the member in terms of mechanical properties shall be done by referring to each member crossing the joint. For this reason, the value of the characteristic length shall be evaluated for each connection involved into the joint. The representation of characteristic length of the most common connections is reported in Fig. 4 with reference to different kinds of joint. Referring to rigidity and ductility, a connection will be finally defined restoring if its generalised force-displacement relationship is "better" than the one of the connected member, this latter calculated on the base of a member length equal to the characteristic length of the connection. It is also to be emphasised that generalised displacement parameters shall be either a deformation or a curvature, depending on whether axial, shear load or moment is involved.

For example, for a typical beam-to column joint subjected to bending action (Fig. 5a), the comparison in terms of initial rotation can be expressed as follows:

$$\varphi_c \leq \chi\left(ML_c / EI_b\right)$$

where, L_c is the characteristic length, M/EI_b is the elastic curvature of the beam for the given bending moment M, and φ_c is the concentrated rotation of the connection under the same bending moment as calculated by means of analytical or experimental procedure. In the application of such procedures, all joint deformation components, elastic and/or plastic, within the zone delimited by the assumed characteristic length, are to be taken into account.

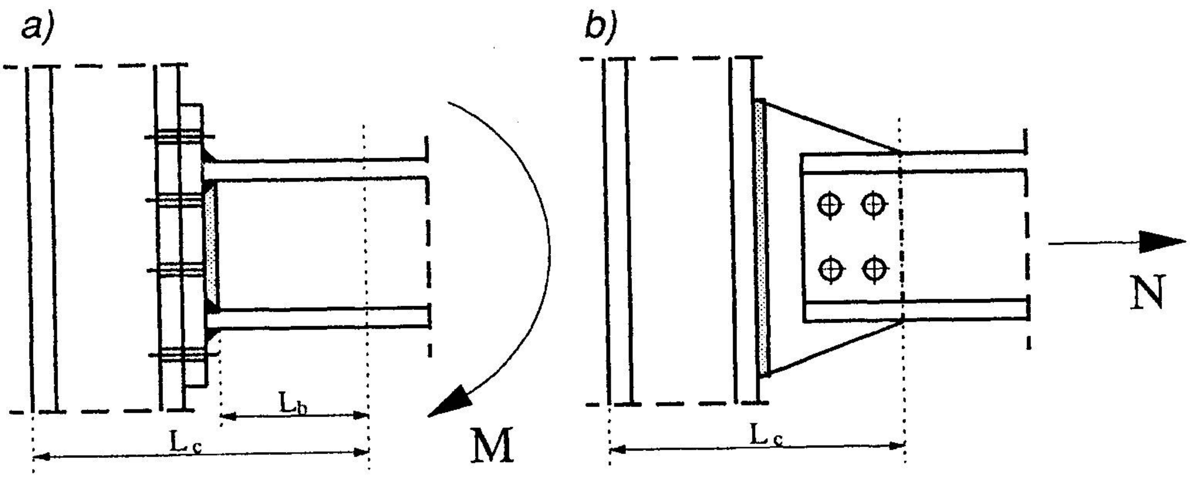

Fig. 5. Characteristic length for bending and axial joints.

Similarly, the assessment of connection axial rigidity may be done through the following inequality (Fig. 5b):

$$\delta_c \leq \chi (NL_c / EA_b)$$

where, L_c is the characteristic length, N/EA_b is the elastic axial deformation of the connected member under the given axial action N, and δ_c is the relative displacement between connected members for the same load.

The coefficient χ is representative of the ratio of connection to member properties which can be accepted to classify the connection as rigid or semirigid. Theoretically, it should be assumed equal to the unit for rigid-to-semirigid limit behaviour, but practically it could be set up on the base of the tolerated effects of joint semirigidity on the behaviour of the structure under consideration. However, it will be never far from the unit value. Similarly, for semirigid-flexible limit behaviour, the χ coefficient must be chosen in such a way that the internal actions as well as the stiffness of connection can be completely disregarded in the structural analysis, with acceptable approximation. At the moment, a suitable approach could be to assume χ=0.1÷0.2, so that the effects of joint flexibility are neglected if its stiffness is lower than the 10÷20% of that of connected member, these latter referred to the characteristic length.

It is to be pointed out that the assessment of connection rigidity can be done also in inelastic range, and not necessarily in term of initial stiffness, as shown in Fig. 6. In this case, the tangent stiffness of the connected member k_m must be considered in the comparison with connection rigidity k_c.

7 Conclusive Remarks and Further Developments

A new classification system for aluminium alloy connections has been proposed. The main aspects of this classification consist in a new approach for the evaluation of connection properties, as well as in a wider generality in terms of considered internal actions. The method is in fact referred to all internal forces and relative displacements and is applicable to all joint

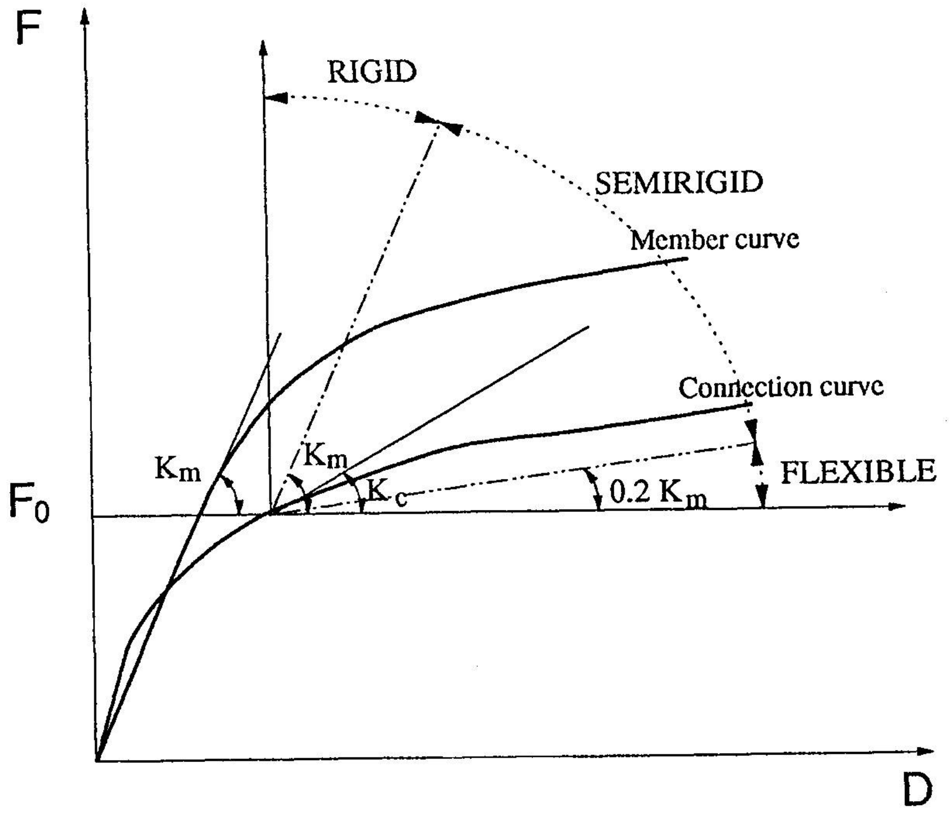

Fig. 6. Connection classification in stiffness.

typologies. In addition, particular attention is paid to the ductility features of the connection, in order to guarantee its capability to accomplish the deformation requirements of a given collapse mechanism.

The joint is classified according to its capability to restore each one of the mechanical properties (initial stiffness, ultimate strength and deformation capacity) of the connected member. Contrary to the EC3 assumptions, which relate the effects of connection to the global behaviour of the structure, the restoring properties are defined on the basis of a local and direct comparison between connection and connected member,. In order to allow such a direct comparison, a new concept of member characteristic length has been stated. It represents the length which has to be considered for the evaluation of generalised displacement parameters of the connected member. The characteristic length is a function of the connection geometry and can be thought as the part of the structure affected by deformation arisen as a consequence of the connection. The connection behavioural class limits has been then fixed on the basis of the above mentioned comparison.

The classification presented herein represents the first step of a more general research project, aimed to set up an appropriate guideline for the design of aluminium alloy structures and, in particular, of connections. This effort is framed within the activity of the CEN TC250/SC9 Committee which, under the chairmanship of F.M. Mazzolani, is preparing the first issue of EC9 "Aluminium Alloy Structures", with the contribution of all Countries of the European Union. The next step of this study will be that to improve the calibration of the proposed approach by means of both experimental and theoretical investigations, devoted to analyse the joint behaviour and the effects of joint semirigidity on the behaviour of the whole structure. The specific allowance for the peculiar features of aluminium alloys is planned to be the basic concern of this research stage, with the expected result to set up a suitable method for evaluating the design moment-rotation characteristic of aluminium alloy joints. For this purpose, an extension of the EC3 method for steel joints is presently being studied, based on the actual non linear behaviour of the material, as well as on the available alloy ductility, which in most cases is lower than in steel. The outcoming of this investigation will contribute to a more effective assessment of this problem in the field of codification, obtained thanks to a more comprehensive approach to both classification of joints and prediction of joint behaviour.

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