

Design of Aluminium Structures

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1. Introductory remarks

The use of aluminium alloys in Structural Engineering is a quite recent activity, also because this family of materials is very young and his history is very short.

The possibility of isolating the aluminium element was foreseen by Sir Humphry Davy at the beginning of 19th Century (1807), but the first concrete result was obtained by Whoeler after 20 years of research (1827). The industrial production of aluminium started just in 1886 as soon as a Frenchman Paul Luis Touissant Hérnoul and an American Charles Martin Hall patented in the same time, but independently, the electrolytic process (Mazzolani, 1985).

The end of 19th Century assisted to a first big challenging structural application: the Schwarz and Zeppeling dirigibles. Since the beginning of 20th Century, aluminium alloys were initially used for applications where there was virtually no substitutive material. The most significant case was the one of the aeronautical industry, where wood and tissues were gradually substituted by the new light metal, giving rise to the basis of the modern aircrafts.

Afterwards, the use of aluminium alloys rapidly spread into many fields both structural and non structural (window frames, door furniture, claddings, industrial chemistry, armaments).

Since many years after World War two, these materials are successfully used in transportation, such as the rail industry (subway coaches, sleeping cars, ...), the automotive industry (containers for trucks, motorcars, moving cranes,...) and the shipping industry (civil and military hydrofoils, motorboats, sailboats, ...).

A parallel trend for aluminium alloys consists on their use in the so-called civil engineering structures, where these materials can be considered as new and they have also to compete with steel, the most widely used metallic material in this field.

In the early Fifties the first building structures made of aluminium alloy appeared in Europe under form of prefabricated systems. At that time, the development of these kind of applications was undermined by the inadequacy or quite complete absence of codification and recommendations, making the structural design difficult for consulting engineers and controlling Bodies.

Nowadays, this limitation has been completely overcome at European level, starting from the first edition of the ECCS Recommendations issued in 1978 by the ECCS Committee T2 (Chairman: F.M. Mazzolani) (Mazzolani, 1980, 1981) and going on at the present time with the preparation of the Eurocode EC9 “Design of Aluminium Structures” by the Technical Committee CEN-TC 250/SC9 (Chairman: F.M. Mazzolani) (Mazzolani, 1998 a,b, 1999, 2001), which is going toward its final configuration, being now progressing the conversion phase (the EN version of EC9 is foreseen for the end of 2004).

What probably is still acting in negative sense is the lack of information about the potential of these materials in structural applications, being their peculiar advantages very seldom considered by structural engineers, who are much more familiar with steel structures, despite the publication of “ad hoc” volumes on the design of aluminium alloy structures (Mazzolani, 1985, 1994, 2003 a,b).

For reducing this gap, a continuous comparison between the two metallic materials, aluminium and steel, is necessary in order to emphasise the specific characteristics and the advantages, as well as sometimes the disadvantages, of aluminium alloys as structural material.

This comparison can lead to identify the design criteria which must be followed in order to make the use of aluminium alloys friendly and actually competitive with steel in the range of structural design.

The main scope of this paper is to briefly present the innovative aspects which characterize the Eurocode 9 on Aluminium Structures with respect to other existing codes (Mazzolani, 1998a,b, 1999a). Starting from the methodology which has been set-up within the range of activity of ECCS (Mazzolani & Frey, 1983; Mazzolani & Valtinat, 1987; Mazzolani, 1995b) during the seventies, new calculation methods have been set-up during the nineties.

First of all, the design rules for the evaluation of internal actions have been given by considering the actual behaviour of the material by means of different degree of refinement in the model of stress-strain relationship, related also to the type of alloy. The analysis of the global performance can be done at different levels from the simplest (linear elastic) to the most sophisticated (generically inelastic with strain-hardening), giving rise to different degrees of reliability.

For the inelastic analysis, a new approximated method has been worked out for practical purposes, being based on the generalization of the well known “plastic hinge” method.

The behaviour of members has been characterized according to four classes, whose definition required the execution of wide range of experimental tests. This classification is still based on b/t ratios, as in EC3 for steel, but the class boundaries have been chosen on the experimental evidence considering the actual response of aluminium alloys.

New calculation methods have been also set up for the verification of local buckling, for the evaluation of rotation capacity and for the design of connections based on a generalized classification system.

Cold-formed and shell structures have been introduced during the conversion phase as autonomous documents.

2. Range of structural applications

The success of aluminium alloys as constructional material and the possibility of a competition with steel are based on some prerequisites which are connected to the physical properties, the production process and the technological features. Summing-up, the following statements can be considered (Mazzolani, 1995b, 1998c, 1999b, 2003a, 2004):

- a. Aluminium alloys represent a wide family of constructional materials, whose mechanical properties cover the range offered by the common mild steels (see Section 3).
- b. Corrosion resistance normally makes it unnecessary to protect aluminium structures, even in aggressive environments.
- c. The lightness of the material gives advantages in weight reduction, but it can be partially offset by the necessity to reduce deformability due to the low elastic modulus, which gives a high susceptibility to instability.
- d. The material itself is not prone to brittle fracture, but particular attention should be paid to those problems in which high ductility is required.
- e. The extrusion fabrication process allows individually tailored shapes to be designed (Figure 1).
- f. As connection solution, either bolting, riveting and welding techniques are available.

After these preliminary remarks, it is possible to state that aluminium alloys can be economical, and therefore competitive, in those applications where full advantage is taken of their above prerequisites. In particular:

A. **Lightness** makes it possible to:

- simplify the erection phases;
- transport fully prefabricated components;
- reduce the loads transmitted to foundations;
- economize energy either during erection and/or in service;
- reduce the physical labour.

B. **Corrosion resistance** makes it possible to:

- reduce the maintenance expenses;
- provide good performance in corrosive environments.

C. **Functionality** of structural shapes, due to the extrusion process, makes it possible to:

- improve the geometrical properties of the cross-section by designing a shape which simultaneously gives the minimum weight and the highest structural efficiency;
- obtain stiffened shapes without using built-up sections, thus avoiding welding or bolting;
- simplify connecting systems among different component, thus improving joint details;
- combine different functions of the structural component, thus achieving a more economical and rational profile.

The best fit from the application side can be obtained in some typical cases, which are characterised in getting profit at least of one of the main basic properties: *lightness, corrosion resistance and functionality*.

The structural applications which best fit these properties in the field of so-called civil engineering are the following:

- a) Long-span roof systems in which live loads are small compared with dead loads, as in the case of reticular space structures and geodetic domes covering large span areas, like halls, auditoriums (Figure 2).
- b) Structures located in inaccessible places far from the fabrication shop, for which transport economy and ease of erection are of extreme importance, like for instance the electrical transmission towers, which can be carried by helicopter completed assembled (Figure 3).
- c) Structures situated in corrosive or humid environments such as swimming pool roofs, river bridges (Mazzolani & Mele, 1997; Mazzolani, 2001b), hydraulic structures and offshore super-structures (Figure 4).
- d) Structures having moving parts, such as sewage plant crane bridges (Mazzolani, 1985a) and moving bridges, where lightness means economy of power under service (Figure 5).
- e) Structures for special purposes, for which maintenance operations are particularly difficult and must be limited, as in case of masts, lighting towers, antennas tower (Mazzolani, 1991) sign motorway portals, and so on (Figure 6).

The above groups mainly belong to the range of the so-called “civil engineering”.

A wider overview of potential applications in the more general range of “structural engineering” is given in Table 1. Each case is located in a given column which can be characterized by one, two or three capital letters. The meaning of the letters is: L for lightness, C for corrosion resistance, F for functionality according to the previous definitions. The combination of these properties identifies the reasons why the use of aluminium alloys can be particularly suitable and even competitive with respect to steel.

3. Aluminium alloys for structural use

Aluminium is not just one material, but it gives rise to a family of different groups of alloys whose mechanical properties widely vary from one group to another and also within each group itself. From the point of view of the technological use, the aluminium alloys can be grouped into eight series, according to the American Association classification, the first of the four digits characterizing the main alloying element and the other three the secondary ones (Mazzolani, 1985b, 1994, 2003 a,b).

- **1000 Series: Pure aluminium**

In this series the aluminium percentage is very high (98.8 to 99 percent). It can be used in low stressed structures under form of plates. Electrical and chemical industries use this series for cables and tanks, due to the high corrosion resistance of the aluminium itself. Its elastic limit is very low ($f_{0.2} \approx 30 \text{ Nmm}^{-2}$), but its ductility is excellent, being the ultimate elongation $\epsilon_t \approx 30$ to 40 percent. If the material is cold-worked, the strength can increase up to $f_{0.2} \approx 100 \text{ Nmm}^{-2}$, whereas the ductility is drastically reduced ($\epsilon_t \approx 3$ to 4 percent).

- **2000 Series: Aluminium-Copper alloys**

These alloys are generally produced under form of profiles, plates and pipes. When submitted to heat-treatment, elastic limit $f_{0.2}$ can increase up to 300 Nmm^{-2} , with a sufficient ductility, being $\epsilon_t \approx 10$ percent. Since the corrosion resistance of these alloys is not very high, it is necessary to protect them especially when used in a corrosive environment. Because of their bad weldability, they are not very popular in structural engineering. Basically, they are used in aeronautical industry with riveted connections.

- **3000 Series: Aluminium-Manganese alloys**

These alloys cannot be heat-treated and they have a slightly higher strength than pure aluminium by keeping a very high ductility, which allows very hard cold-forming processes for increasing strength. They are corrosion resistant. Specific applications are panels and trapezoidal sheeting for roofing systems.

- **4000 Series: Aluminium-Silicon alloys**

The properties of these alloys are similar to those of the 3000 series. However, they are not often used, except for welding wires.

- **5000 Series: Aluminium-Magnesium alloys (5000 series)**

Even though these alloys cannot be heat-treated, their mechanical properties could be higher than those corresponding to the 1000, 3000 e 4000 series. The strength can be increased when they are cold worked, being the elastic limit $f_{0.2}$ up to 200 Nmm^{-2} and the ductility still quite high (ϵ_t up to 10 percent). The corrosion resistance is also high, especially in marine environment, when the amount of Mg is less than 6 percent. These alloys are often used in welded structures, since their strength is not drastically reduced in the heat-affected zone.

- **6000 Series: Aluminium-Silicon-Magnesium alloys**

By means heat-treatment the strength of these alloys is increased up to $f_{0.2} \approx 250 \text{ Nmm}^{-2}$, with a quite good ductility, being ϵ_t up to 12 percent. These alloys are corrosion resistant. They are particularly suitable for extrusion, but also rolled sections as well as tubes can be produced. These alloys are used either in welded structures and in bolted or riveted connections.

- **7000 Series: Aluminium-Zinc alloys**

These alloys are produced under form of both extruded and rolled heat-treated profiles. They can be subdivided into two sub-families depending upon the percentage of copper as the third alloying element:

- AlZnMg alloys reach a remarkable strength, being the elastic limit $f_{0.2}$ greater than 250 Nmm^{-2} , with a quite good ductility ($\epsilon_t \cong 10$ percent). They are also corrosion resistant. These alloys are generally used in structural applications, because they are particularly suitable in welded structures owing to their self-tempering behaviour, which allows to recover the initial strength in the heat-affected zone.
- AlZnMgCu alloys are the highest resistance alloys after heat-treatment, reaching $f_{0.2} \cong 500 \text{ Nmm}^{-2}$; conversely, they have low weldability and are not corrosion resistant, because of the presence of copper, therefore requiring protection by plating or painting.

- **8000 Series: Aluminium-Iron-Silicon alloys**

This series is preferably used as material for packaging but, due to its advantages in fabrication, it finds more and more application in building industry especially for facades.

4. Comparing Aluminium with Steel

There are many reasons for the selection of a material for structural applications, but the determinant issue is that the product must be affordable, i.e. its cost must be acceptable to the customer. Generally, aluminium is attractive in many applications, because of a favourable life-cycle cost, which is given by the sum of the initial cost of the finished product, the cost of operating or maintaining the product over its life and the cost of disposing of or recycling it after its useful life. In addition, aluminium has sustained and increased its use in many fields, partly because the price for aluminium relative to that for steel, overall, has decreased gradually over the 100-year life of the aluminium industry.

A comprehensive comparison with steel, not only in term of cost, is important in order to clearly identify the conditions under which and the field of application where aluminium alloys can be competitive.

The main pre-requisites of aluminium are (Mazzolani, 1985 b, 1994, 1999b, 2003 a,b):

- *Lightness.* The specific weight is $\gamma = 2700 \text{ kgm}^{-3}$, equal to one-third that of steel;
- *Corrosion resistance.* The exposed surface of aluminium combines with oxygen to form a thin inert aluminium oxide film which blocks further oxidation. Contrary, steel must be always corrosion protected in any kind of environment.

From the point of view of mechanical resistance, as it has been emphasized in the previous Section 3, aluminium alloys series form a big family of materials, where the elastic limit widely varies from 30 Nmm^{-2} (pure aluminium) to 500 Nmm^{-2} (AlZnMgCu alloy) and the ultimate elongation in many cases, but not always, lies in a suitable or at least acceptable range for structural applications.

Table 2 shows a summary comparison among some aluminium alloys extrusions (one work-hardened 5083 F ; two heat-treated 6063 T6 and 7020 T6) and the most commonly used mild steels for hot-rolled sections (S235, S275 and S355). The main mechanical properties are compared here: elastic limit ($f_{0.2}$) or yield stress (f_y), ultimate strength (f_t), Young's modulus (E), ultimate elongation (ϵ_t), specific weight (γ) and thermal elongation coefficient (α).

From the comparison of the two typical stress-strain curves, it can be observed that (Figure 7):

- Both materials behave linear elastically with a different slope of the σ - ε curve up to the elastic limit $f_{0.2}$ for aluminium and the yield stress f_y for steel ; this part of the curve basically covers the working range of structures , the only difference between the two materials being the slope of the curve.
- After the elastic range, aluminium alloys have a continuous strain-hardening behaviour which is not preceded by a perfectly plastic branch corresponding to yielding plateau as for steel;
- The ultimate deformation for aluminium alloys is lower (around 8-12 %) than the one of steel (greater than 20 %) ;
- The $f_t/f_{0.2}$ ratio for aluminium alloys is normally lower than the one of steel, depending on the degree of hardening.

A generalized $\varepsilon=\varepsilon(\sigma)$ relationship for aluminium alloys is the so-called Ramberg-Osgood law (Mazzolani, 1994):

$$\varepsilon = \frac{\sigma}{E} + 0.002 \left(\frac{\sigma}{f_{0.2}} \right)^n$$

where

E is the Young's modulus and $f_{0.2}$ is the elastic limit at a residual strain of 0.2%.

The exponent n of the Ramberg-Osgood law is given by

$$n = \frac{\ln 2}{\ln \left(\frac{f_{0.2}}{f_{0.1}} \right)}$$

where $f_{0.1}$ is the stress at a residual strain of 0.1%.

Depending on the ratio $f_{0.2}/f_{0.1}$, which characterises the “knee” of the σ - ε curve, the values of n are useful to classify aluminium alloys from the point of view of the strain-hardening rate of the stress-strain behaviour.

In fact, when the ratio $f_{0.2}/f_{0.1}$ tends to 1, the exponent n tends to infinity and the Ramberg-Osgood law represents the mild steel behaviour. Contrary, $n=1$ provides a linear elastic behaviour. Intermediate values of n express the different behaviours of aluminium alloys, by means of decreasing values of n as far as the rate of strain-hardening increases.

An effective interpretation of structural materials by means of the exponent n of the Ramberg-Osgood law is given in Figure 8 as a function of the $f_{0.2}/f_{0.1}$ ratio , where aluminium alloys are identified by means of the classical Sutter's classes. In general, it can be observed that this law can be suitably used also to represent all round-type metallic material, i.e. stainless steel.

An important parameter for comparing structural materials is the ratio f_0/γ between strength and specific weight γ , being the reference strength f_0 equal to f_y for steel and to $f_{0.2}$ for aluminium alloys. This ratio, multiplied by 10^5 cm, is about 3 to 4.5 for mild steels, whereas it can vary from 8 to 17 for aluminium alloys, giving a good forfeitary index of the material utilization, which is extraordinary advantageous for aluminium alloys.

However, it is not always possible to completely take advantage of this structural benefit offered by aluminium alloys, especially when the material is loaded in compression, because, due to the smaller value of the Young's modulus, the instability phenomena are more likely to occur than in steel structures and, therefore, more dangerous.

Further observations regarding aluminium alloy structures have to be pointed out:

- The structures made of aluminium alloys are more sensitive to thermal variations, because the coefficients of thermal expansion of this metal is twice the one of steel; this fact has to be taken into account particularly when designing support apparatus;

- Contrary, residual stresses produced by constraining thermal deformations are about 30 percent lower than those in steel structures, because they are proportional to the product αE ;
- Aluminium alloy structural components can be manufactured by rolling, extrusion, casting and drawing processes. The extrusion process is of particular interest as it allows fabrication of profiles of any shape (Figure 1), contrary to steel whose shapes are standardized, being limited by the hot-rolling process.

5. International research and codification

Owing to the increasing use of aluminium alloys in construction, several countries have published specifications for the design of aluminium structures. It is due to the efforts of the ECCS Committee for Aluminium Structures and of its working groups that the first edition of the European Recommendations for Aluminium Alloy Structures became available in 1978 (Mazzolani, 1978, 1981a). These Recommendations represent the first international attempt to unify computational methods for the design of aluminium alloy constructions in civil engineering and in other applications, by using a semi-probabilistic limit state methodology. Immediately after during the eighties the UK (BS 8118), Italian (UNI 8634; Atzori & Mazzolani, 1983), Swedish (SVR), French (DTU), German (DIN 4113) and Austrian (ON) specifications have been published or revised.

In the last decade, the Aluminium Association Recommendations in USA have been up-dated and the ultimate limit state design has been introduced beside the traditional allowable stress design. A new edition of the Canadian Code has been recently set-up on the bases of an ISO technical document produced by the Committee TC 167.

Since 1970 the ECCS Committee on Aluminium Alloy Structures has carried out extensive studies and research, in order to investigate the mechanical properties of materials, their imperfections and their influence on the instability of members (Mazzolani & Valtinat, 1987). On the basis of these data, for the first time, the aluminium alloy members have been characterized as “industrial bars”, in accordance with the current trends of the safety principles in metallic structures (Mazzolani, 1974; Mazzolani & Frey, 1977; De Martino et al., 1985; Mazzolani, 1980) (see Section 7).

Among the research programs in this fields, undertaken with the cooperation and support of several European countries, buckling tests on extruded and welded built-up members were carried out at the University of Liège, in cooperation with the University of Naples and the Experimental Institute for Light Metals of Novara, Italy (Gatto et al., 1979; Mazzolani, 1981b).

The use of “ad hoc” simulation methods which allow all the geometrical and mechanical properties, together with their imperfections to be taken into account, has led to satisfactory results in the study of the instability phenomena of columns and beam-columns. The analysis of these experimental and numerical results demonstrated the major differences between the behaviour of steel and aluminium. In particular the buckling curves (Mazzolani, 1981b; Mazzolani & Frey, 1983; Mazzolani & Piluso, 1990), valid for extruded and welded bars with different cross-sections and different alloys, have been defined and they have been used in many national and international Codes, including ISO and Eurocode.

During the 80's the extension of the principles of plastic design has been successfully done (Mazzolani, 1984; Mazzolani et al., 1985; Cappelli et al., 1987). The main results have been utilized also in the preparation of Eurocode 9.

In the last decade the research reached satisfactory levels also in other fields, such as the local buckling of thin plates and its interaction with the global behaviour of the bar, the instability

of two-dimensional elements (plates, stiffened plates, web panels) and the post-buckling problems of cylindrical shells (Mandara & Mazzolani, 1989, 1990; Mazzolani et al., 2003a,b; Mazzolani & Mandara, 2004).

A new field of interest for structural application has been investigated in the composite aluminium-concrete system. Encouraging results have been obtained, but not sufficient for a codification (Bruzzeze et al., 1989, 1991).

6. The main features of Eurocode 9

The unavoidable complexity of a code on Aluminium Structures is essentially due to both the nature of the material itself (much more “critical” and less known than steel), which involves the solution of difficult problems and demands careful analysis. In this case the need for the code to be educational as well as informative and not only normative has been particularly determinant (Mazzolani, 1998a, 1999a).

The ENV edition of Eurocode 9 “Design of Aluminium Structures” (1998) was composed by three documents (Part 1.1 “General rules”, Part 1.2 “Structural fire design” and Part 2 “Structures susceptible to fatigue”).

For an explicit request of the European Aluminium Association (EAA), two new items have been added in the conversion phase: cold-formed sheeting and shell structures, as the Aluminium Industry is particularly interested in both these fields of applications.

The PTs for the conversion phase from ENV to EN started to work in 2001, on the basis of the remarks collected in the meantime. This phase will end in 2005 and the final version of Eurocode 9 will be composed by five documents:

-Part 1.1 “General rules”

-Part 1.2 “Additional rules for fire design”

-Part 1.3 “Additional rules for structures susceptible to fatigue”

-Part 1.4 “Supplementary rules for cold-formed sheeting”

-Part 1.5 “Supplementary rules for shell structures”.

Contrary to the others Eurocodes, Eurocode 9 consist in one Part only, which is split in one basic document “General rules” and four specific documents, which are related to the basic one. No mention to specific types of structures, like in steel (i.e. bridges, towers, tanks,...), but just general items which are applicable not only to the range of the so-called “Civil Engineering”, but more widely to any kind of structural applications, including the Transportation Industry.

The preparation of the Eurocode 9 has been based on the most significant results which has been achieved in the field of aluminium alloy structures, without ignoring the previous activities developed within ECCS and in the revision of outstanding codes, like BS 8118.

The ECCS method for column buckling has been utilised also in EC9 with just some small editorial changes. It is based on the use of two buckling curves (a and b), which cover extruded profiles made of heat-treated and work-hardened alloys, respectively (Mazzolani, 1994, 1995a).

In general, checks for beams, columns and beam-columns have been provided considering the specific features of aluminium alloys (Mazzolani & Valtinat, 1992).

For welded profiles, the lowering effects of heat-treated zones have been taken into account by means of appropriate reduction factors. This method was based on the experimental evidence which allowed to characterise the aluminium alloy members as “industrial bars” (see Section 7).

An innovative issue of Eurocode 9 Part 1.1 “General Rules” is given by the introduction, for the first time in a structural aluminium code, of the analysis of the inelastic behaviour starting

from the cross-section up to the structure as a whole (Mandara & Mazzolani, 1995; Mazzolani & Piluso, 1995; De Matteis et al., 1999b; Mazzolani et al., 1999b).

The classification of cross-section has been done on the basis of experimental results, which come from an “ad hoc” research project supported by the main representatives of the European Aluminium Industry, which provided the material for specimens.

The output has been the set-up of behavioural classes based on the b/t slenderness ratio, according to an approach qualitatively similar to the one used for steel, but with different extension of behavioural ranges, which have been based on the experimental evidence (Mazzolani et al., 1996a, 1999a, 2000a, 2001b, 2003c) and confirmed by numerical simulation (Mazzolani et al., 1997c; De Matteis et al., 2001c, 2002a) (see Section 8).

The evaluation of the resistance of cross-sections has been introduced in an unitary way with specific reference to the limit states which the behaviour of the four classes are concerned to (see Section 9).

For members of class 4 (slender sections), the check of local buckling effect is done by means of a new calculation method which is based on the effective thickness concept. Three new buckling curves for slender sections has been assessed considering both heat-treated and work-hardened alloys, together with welded and non-welded shapes (Landolfo & Mazzolani, 1995, 1998; Mazzolani et al., 1997a, 1998) (see Section 10). This method represents the basic starting point for the detailed treatment of cold-formed sheeting as given in Part 1.4 “Supplementary rules for cold-formed sheeting”.

The problem of the evaluation of internal actions has been faced by considering several models for the material constitutive law from the simplest to the most sophisticated, which give rise to different degrees of approximation. The global analysis of structural systems in inelastic range (plastic, strain hardening) has been based on a simple method which is similar to the well known method of plastic hinge, but considers the typical parameters of aluminium alloys, like absence of yielding plateau, continuous strain-hardening behaviour, limited ductility of some alloys (Mazzolani, 1994) (see Section 11).

The importance of ductility on local and global behaviour of aluminium structures has been emphasised, due to the sometime poor values of ultimate elongation, and a new “ad hoc” method for the evaluation of rotation capacity for members in bending has been set up (Mazzolani & Piluso, 1995; De Matteis et al., 1999b, 2002a) (see Section 12).

For the behaviour of connections, a new classification system has been proposed according to strength, stiffness and ductility (Mazzolani et al., 1996b; De Matteis et al., 1999a) (see Section 13).

Based on the experimental evidence on monotonic and cyclic test, a new method for the strength evaluation of T-stub connections has been set-up and introduced in Part 1.1 (Mazzolani et al., 2000b; De Matteis et al., 1999c, 2001a,b, 2002b, 2003).

The new Part 1.5 “Supplementary rules for shell structures” dealing with shell structures has been built-up by following the same format of the similar document in EC3, but the calculation method are based on appropriate buckling curves which are obtained by the experimental evidence on aluminium shells (Mandara & Mazzolani, 1989, 1990; Mazzolani et al., 2003 a,b; Mazzolani & Mandara, 2004).

Fire Design is a transversal subject for all Eurocodes dealing with structural materials and it is located in Part 1.2 “Additional rules for fire design”. For Aluminium Structures it has been codified for the first time according to the general rules which assess the fire resistance on the bases of the three criteria: Resistance (R), Insulation (I) and Integrity (E).

As it is well known, aluminium alloys are generally less resistant to high temperatures than steel and reinforced concrete. Nevertheless, by introducing rational risk assessment methods, the analysis of a fire scenario may in some cases result in a more beneficial time-temperature relationship and thus make aluminium more competitive and the thermal properties of

aluminium alloys may have a beneficial effect on the temperature development in the structural component (Mazzolani, 1994).

The knowledge on the fatigue behaviour of aluminium joints has been consolidated during the last 30 years (Mazzolani, 1994). In 1992 the ECCS Recommendations on Fatigue Design of Aluminium Alloy Structures have been published, representing a fundamental bases for the development of Eurocode 9 (Mandara et al., 1992; Mazzolani & Grillo, 1995). It was decided to characterise Part 1.3 “Additional rules for structures susceptible to fatigue” of EC9 in general way, giving general rules applicable to all kind of structures under fatigue loading conditions with respect to the limit state of fatigue induced fracture. It has been done contrary to steel, for which Part 2 is dealing with bridges only. Three design methods has been introduced:

- Safe life design
- Damage tolerant design
- Design assisted by testing

The following basic groups of detail categories have been considered:

- non-welded details in wrought and cast alloys;
- members with transverse welded attachments;
- members with longitudinal welded attachments;
- welded joints between members;
- crossing welds/built-up beams
- mechanically fastened joints;
- adhesively bonded joints.

The use of finite elements and the guidance on assessment by fracture mechanism have been suggested for stress analysis.

The importance of quality control on welding has been particularly emphasised in general and specific reference to pr EN 1090 “Execution of steel and aluminium structures” has been taken into consideration.

7. Characterization of “industrial bar”

The results of the imperfection measurements have been used to calibrate the simulation methods which were used for the evaluation of the load carrying capacity of members (Mazzolani, 1994).

Summing-up, the aluminium alloys bars, due to their fabrication process, are affected by the following types of geometrical and mechanical imperfections, characterizing the “industrial bar” (Mazzolani, 1995a):

a) geometrical imperfections:

- Out-of straightness of aluminium extruded bars is usually less severe than in steel, being limited by the value of about $L/2000$; in case of welded bars this value decreases to $L/3000$.
- Variations of dimension are present in the extruded tubes, where the scatter in thickness reaches 9 percent; in case of welded double T profiles the eccentricity of the webs in the weak axis direction reaches the value of $L/1600$, but when added to initial out-of-straightness never overcomes the value of $L/1000$, which can be considered as an upper bound to be used in calculations.

b) mechanical imperfections

- Residual stresses in the extruded profiles of any shape, whatever the heat-treatment, have very low values, so they have a very small effect on load-bearing capacity and for practical purposes they can be neglected. On the contrary, they are not negligible in welded profiles,

where the elastic limit of the welding metal is reached near the welds. So, their influence must be taken into account in checking stability, even if in average the residual stress distribution in aluminium alloy is less severe than in steel.

- Distribution of mechanical properties can be considered highly homogeneous in extruded profiles and therefore ignored. On the contrary, in case of welded shapes the distribution is strongly influenced by the technological treatment, giving rise to different lowering effect near the weld. In case of work-hardened alloys the decrease of strength is about 10 percent, but in case of heat-treated alloys it reaches 40-50 percent. Near the weld, three regions can be identified, having different stress-strain curves:
 - unaffected parent metal
 - partially affected parent metal
 - heat-treated zones around the weld metal (HAZ)

For the heat-treated zones HAZ in welded sections the actual distribution of the proof stress must be, therefore, considered in the evaluation of load-bearing capacity, by means of appropriate models.

The lowering effects due to HAZ on the load carrying capacity of aluminium alloy welded members have been carefully taken into account in EC9, in both strength and stability checks.

8. Classification of cross-sections

The behaviour of members strictly depends on the shape of the cross-section and, therefore, the model to be used in structural analysis must be related to the capability of members to reach a given limit state, such as:

- a) **elastic buckling limit state**, characterised by the onset of local instability phenomena in the compressed parts of the section;
- b) **elastic limit state**, corresponding to the attainment of the proof stress in the most stressed fibres of the cross-section;
- c) **plastic limit state**, corresponding to the complete yielding of the cross-section under the hypothesis of elastic perfectly plastic material;
- d) **collapse limit state**, corresponding to the actual full strength of the cross-section considering hardening effects.

These limit states definition corresponds to the one of steel sections in EC3. In EC9 it was decided to keep the same definition already well-known for steel, by quantifying the behavioural ranges in different way according to the experimental evidence.

Therefore, in Eurocode 9, with reference to the above limit states, aluminium cross-sections are divided in four classes (Figure 9):

Class 1: ductile sections, which develop all the collapse resistance without any problem of local buckling and with the full exploitation of the hardening properties of material until the ultimate value of deformation depending on the type of alloy (limit state d).

Class 2: compact sections, which are capable to develop the plastic ultimate resistance without full exploitation of the hardening properties of material which is prevented by the onset of plastic instability phenomena (limit state c).

Class 3: semi-compact sections, which are capable to develop the elastic limit resistance only without getting into inelastic range owing to instability phenomena which prevent the development of important plastic deformations, giving rise substantially to a scarcely ductile behaviour (limit state b).

Class 4: slender sections, whose behaviour is governed by the occurring of local buckling phenomena, which produce a reduction of the effective resistant section without plastic

deformations, giving rise to a remarkably brittle behaviour (limit state a).

Figure 9 shows the generalised force F versus displacement D curves, corresponding to the above defined behavioural classes.

As reference parameter to decide which class a given cross-section belongs to, the b/t ratio is conventionally assumed, like in steel, but with different values.

The following limits have been assumed in Eurocode 9:

class 1: $b/t \leq 11$

class 2: $11 < b/t \leq 16$

class 3: $16 < b/t \leq 22$

class 4: $b/t > 22$

They are based on the experimental evidence coming from an “ad hoc” research programme on hollow, rectangular and square sections, channels and angles (Mazzolani et al., 1996a, 1999a, 2000a, 2001b, 2003c).

Figure 10 shows the normalised stress-strain curves from stub column tests on hollow sections belonging to the four behavioural classes and Figure 11 identifies the b/t ratios corresponding to the boundary of the four classes, as given above.

Eurocode 3 gives the values of the slenderness parameters β_1/ε , β_2/ε , β_3/ε , being $\varepsilon = (250 / f_{0.2})^{0.5}$, which identify the limits of the four classes, considering the presence of welds and the type of alloy, being basically class A for heat-treated alloys having $n > 10$ and class B for non heat-treated alloys having $n < 10$ (see Table 3).

These values allow the classification of parts of cross-section which can be internal or outstand. The evaluation of the parameter b as a function of the b/t ratio of each part t is given by means of appropriate formulae which take also into account the stress gradient and the different local buckling modes.

9. Resistance of cross-sections

9.1. Evaluation of ultimate axial load

The load-bearing capacity of cross-sections under axial compression, excluding overall buckling phenomena of the member, can be evaluated with reference to the above mentioned limit states and the corresponding behavioural classes (Mazzolani, 1998b).

The value of axial load for a given limit state can be expressed by the generalized formula:

$$N = \alpha_{Nj} A f_d$$

being:

f_d the design value of strength $= (f_{0.2} / \gamma_m)$

A the net cross sectional area

α_{Nj} a correction factor, given in Table 4, depending on the assumed limit state.

where A_{eff} is the effective cross sectional area, evaluated accounting for local buckling phenomena. When welded sections are involved, a reduced value A_{red} of the net cross sectional area shall be used, evaluated by accounting for HAZ.

In case of flexural buckling, the ultimate resistance is given by

$$N = k \chi A f_d$$

where

χ is the reduction factor for the relevant buckling mode;

k is a factor to allow for the weakening effects of longitudinal welding

The non dimensional buckling curves are given in Figure 12, where curve 1 is used for heat-treated alloys (class A) and curve 2 for work-hardened alloys (class B).

9.2. Evaluation of ultimate bending moment

The load-bearing capacity of cross-sections under bending moment can be evaluated with reference to the above mentioned limit states and the corresponding behavioural classes (Mazzolani, 1998b).

The value of bending moment for a given limit state can be expressed by the generalized formula:

$$M = \alpha_{Mj} W f_d$$

being:

f_d the design value of strength $= (f_{0.2} / \gamma_m)$

W the elastic section modulus

α_{Mj} a correction factor, given in Table 5, depending on the assumed limit state, where:

$n = f_{0.2}$ (in daNmm^{-2}) is the exponent of Ramberg – Osgood law representing the material behaviour (see Section 4);

α_5 and α_{10} , are the generalized shape factors corresponding to ultimate curvature values $\chi_u = 5\chi_{el}$ and $10\chi_{el}$ respectively, being χ_{el} the elastic limit curvature (the value 5 or 10 is assumes considering the ductility of the alloy);

α_0 is the geometrical shape factor;

Z is the plastic section modulus;

W_{eff} is section resistance modulus evaluated accounting for local buckling phenomena.

When welded sections are involved, reduced value W_{red} and Z_{red} of section resistance and plastic modulus shall be used, evaluated by accounting for HAZ.

10. The approach for slender sections

The effect of local buckling in slender members (section class 4) is allowed for by replacing the true section by an effective one, which is obtained by using a local buckling coefficient ρ_c to factor down the thickness of any slender element that is wholly or partly in compression. The coefficient ρ_c is provided through curves as a function of the factor β/ϵ , being β a slenderness parameter which depends both on b/t ratio and stress gradient for the element concerned and $\epsilon = (250/f_{0.2})^{0.5}$.

Three design curves (Figure 13) have been proposed referring to the following cases (Landolfo & Mazzolani, 1998):

Curve a: unwelded elements in heat-treated alloy (class A, $n > 10$);

Curve b: welded elements in heat-treated alloy (class A, $n > 10$) and unwelded plates in non heat-treated alloy (class B, $n < 10$);

Curve c: welded elements in non heat-treated alloy (class B, $n < 10$).

According to EC9, a preliminary distinction between internal and outstand elements gives rise to the design curves expressed in the general form:

$$\rho_c = \frac{c_1}{\beta/\epsilon} - \frac{c_2}{(\beta/\epsilon)^2}, \quad \text{with } \beta > \beta_3 \quad (\text{see Section 8})$$

being c_1 and c_2 two coefficients, whose values are approximately given in Table 6.

This methodology, based on the reduced thickness approach, is applied to typical cold-formed sheetings in Part 1.4 (Figure 14).

11. Evaluation of internal actions

Some indications regarding the methods of global analysis both elastic and plastic, to be used in the calculation of structures are provided in EC9.

Elastic global analysis relies on the assumption that the stress-strain relationship of the material is linear up to failure, independently of the stress level. This assumption may be kept for both first order and second order analysis, even when the resistance of the cross sections is evaluated according to its ultimate load bearing capacity in post-elastic range. In order to take into account the plastic moment redistribution within the structure, the peak elastic moment can be increased or decreased by up to 15%, provided the new internal forces and moments remain in equilibrium and the cross section have sufficient ductility to allow for the plastic redistribution. For this reason all members, where the moments are reduced, must have Class 1 or at least Class 2 cross-section. When such conditions are fulfilled, then elastic global analysis can be used in all cases.

For more refined calculation, elastic global analysis may be also applied by assuming that the stress-strain relationship of the material is not linear, the value of the instantaneous tangent modulus depending on the stress level, but the exploitation of the inelastic behaviour of material can be allowed just for members having cross-section of Class 1 or Class 2.

The characterization of the law of the material must take into account the actual strain-hardening behaviour of the alloy. To this purpose, Eurocode 9 (Annex B) gives some analytical models, from the more simple (piecewise bi – or three-linear with and without hardening (see Figure 15), to more sophisticated (continuous models), according to the Ramberg-Osgood law (see Figure 16).

Plastic global analysis may be used only when member cross sections satisfy requirements specified for Class 1 cross-sections and provided that the aluminium alloy has sufficient ductility. Cross-section of Class 2, 3 and 4 are not allowed. For Class 1 cross-sections the check of the deformation capacity is required in relation to the ductility demand of the structural scheme.

Plastic analysis may be carried out by assuming for the material the following behavioural models:

- Rigid-Perfectly plastic;
- Elastic-Perfectly plastic;
- Inelastic-Perfectly plastic.

The three models differ each other by the assumption made on the material behaviour in the elastic range, which can be either rigid, elastic or inelastic. When it is assumed to be rigid, then elastic deformations of cross-sections, members and foundations may be neglected and all plastic deformations are assumed to be concentrated at plastic hinge location. It can be used when the elastic pre-collapse deformations are comparatively small and their magnitude is not so relevant as to involve second order effects.

In the elastic-perfectly plastic analysis, the behaviour of material is assumed to be linear up to a limit level of stress corresponding to the yielding. As a consequence of this, the behaviour of the cross-sections can be generally assumed to be elastic-plastic as well, at least for small values of the geometrical shape factor ($\alpha < 1.2$). As a consequence of this, it is possible to assume that the plastic deformations are concentrated in correspondence of the plastic hinge

location. The transition from elastic to plastic range will be more or less gradual depending on both load condition and section shape.

A more generality can be achieved if the elastic branch of the material law is assumed to be non linear, as in the third one of the above cases. Accordingly, the non linear behaviour of sections is considered in the evaluation of the deformation occurring in a given member before the formation of the plastic hinge. For this method, a discretized F.E.M. approach is recommended, in order to closely represent the non linear behaviour of the structure.

In addition, the effect of strain hardening can be taken into account by substituting the horizontal plastic branch, with an increasing one, evaluated according to the hardening feature of the alloy. The following options are covered:

- Rigid-Hardening;
- Elastic-Hardening;
- Generically inelastic.

Rigid- and elastic-hardening analyses are quite similar to the corresponding rigid- and elastic-plastic ones, in the sense that they are based on a concentrated plasticity model relying on the concept of plastic hinge. The main difference stands in the evaluation of the post-elastic response, which depends on the hardening feature of the alloy, as well as on its available ductility. For this reason, the analysis is assumed to be concluded when a given limit value of deformation is reached in the material.

In the most general case of structural analysis, called “Generically inelastic”, both material and sections are idealized according to their actual stress-strain and generalized force-displacement relationship, respectively. The transition from the elastic to the plastic range is gradual and the achievement of the ultimate limit state is defined by the attainment of a given limit values of strength or deformation. Contrary to the all previous cases, the “Generically inelastic” approach cannot adopt the simple concentrated plasticity idealization, based on the concept of plastic hinge, but should use refined discretized approaches, e.g. F.E.M. simulation, to display the whole of its accuracy in the prediction of structural inelastic behaviour.

For practical purpose, Eurocode 9 in Annex E gives a simple approach for plastic analyses for structures whose collapse occurs due to the attainment of ultimate deformation in a certain number of sections. It is a “plastic hinge method for continuous beams”, very familiar in steel, which is based on the elastic-perfectly plastic behaviour of material.

The ultimate moment is defined as:

$$M_u = \eta \cdot \alpha_\xi \cdot f_{0.2} \cdot W$$

where

η is an appropriate correction factor;

α_ξ is the generalized shape factor, taking into account the material hardening effect and depending on the ductility feature of the alloy.

The values of η have been evaluated on the bases of a parametric analyses in which the approximate plastic hinge method has been compared with the results of the application of a discretized method (Figure 17).

The evaluation of ductility demand is conventionally given by considering two limits values for the curvature χ_u , based on the ultimate tensile deformation:

$$\chi_u = 5 \cdot \chi_e \text{ for brittle alloys } (4\% \leq \epsilon_u < 8\%)$$

$$\chi_u = 10 \cdot \chi_e \text{ for ductile alloys } (\epsilon_u > 8\%)$$

Figure 18 shows the values of η as a function of the above limit curvatures, the geometrical shape factor α_0 and the exponent n_p of the Ramberg-Osgood law in plastic range.

12. Evaluation of ductility demand

The possibility to a reliable application of plastic global analyses methods, i.e. the above plastic hinge method, is based on the balance between demand and availability.

Rules for the evaluation of the available rotation capacity are supplied in Annex D of Eurocode 9, referring to Class 1 cross-sections only. They can be used also for the evaluation of the ultimate strength of Class 2 and 3 section, provided that no local buckling phenomena occur.

The rotation capacity is given as a function of numerical parameters m and k in the form (see Figure 19):

$$R = \alpha_{M,j} \left(1 + 2 \frac{k \cdot \alpha_{M,j}^{m-1}}{m+1} \right) - 1$$

being $\alpha_{M,j}$ provided in Table 5 of Section 9.2 (Mazzolani, 1994; Mazzolani & Piluso, 1995).

The ductility demand of a given structure under the design loads can be evaluated in several ways, depending on how the external actions are applied to the structures. A rigorous definition of the ductility demand is only possible if the load is applied to the structure through a system of impressed displacements. In this case, regardless of the structure strength capability, the ductility demand can be defined as the maximum value of a deformation parameter which the structure is able to reach in a load process in which a generical displacement parameter is assumed as independent variable. However, in most cases, the structure is loaded by means of a force system increasing up to collapse. In such conditions, the ductility demand would be nominally infinite, because when the ultimate value of load is attained, the structure has no longer possibility to resist the external loads and the plastic flow into the collapsed sections would be unlimited. Thus, the ductility demand can be defined only in a conventional way. For generical truss- or beam-made structures, three ways to evaluate the ductility demand can be followed:

- 1) The ductility demand is defined as the required rotation in the most developed plastic hinge when the plastic mechanism is attained. The structure is solved by means of a concentrated plasticity approach based on the concept of plastic hinge. The maximum required strain can be evaluated provided that as convenient length for the plastic hinge is assumed.
- 2) The ductility demand is defined as the required rotation in the most developed plastic hinge evaluated when the plastic hinge idealization provides the same load bearing capacity as predicted by a more accurate, inelastic method of analysis based on a discretized model. In this case the structure should be solved by means of both methods, in order to compare the obtained results.
- 3) The ductility demand is not evaluated on the base of the structural scheme, but it is defined “a priori” as a function of the maximum elastic strain of the alloy. The corresponding load bearing capacity can be evaluated in a simpler way by applying the plastic hinge method in which a modified value of the conventional yield stress is adopted, in order to take into account the actual behaviour of the alloy in terms of both available ductility and strain hardening.

The first method is purely conventional, since is based on a concentrated plasticity idealization, which hardly corresponds to the actual structural behaviour at collapse. The second one requires for the structure to be calculated two times, with a concentrated plasticity approach, as well as with a F.E.M. numerical simulation. For this reason, it would result in a higher computation cost, which is not suitable for practical application. Eventually, the third one, could represent a good method for an accurate inelastic analysis of aluminium alloy structures, without disregarding the actual mechanical features of the material. Furthermore, because of its inherent simplicity, it can be profitably used as a design method for structures at

the ultimate limit state. In fact, from the point of view of application, it is quite similar to the classical plastic hinge method applied for steel structures. EC9 provides some indications about the use of such method for the plastic analysis of continuous beams, by considering the actual mechanical properties of the different aluminium alloys.

13. Design of joints

As proposed by Eurocode 9 in Annex J, connections may be classified according to their capability to restore the behavioural properties (elasticity, rigidity, strength and ductility) of the connected member (Mazzolani et al., 1996b). With respect to the global behaviour of the connected member, two main classes are defined:

- *Fully restoring connections*, where the behavioural properties are always higher than those of the connected member.
- *Partially restoring connections*, where the behavioural properties do not reach those of the connected member.

As behavioural properties of connections we intend the triad “rigidity, strength and ductility”. With respect to the single behavioural property of the connected member, the following classifications can be assumed (Figure 20).

Classification according to rigidity (Figure 20b)

- Rigidity restoring connections (rigid)
 - Rigidity non-restoring connections (semi-rigid)
- depending on whether the initial stiffness of the connected member is restored or not, regardless of strength and ductility.

Classification according to strength (Figure 20c)

- Strength restoring connections (full strength)
 - Strength non-restoring connections (partial strength)
- depending on whether the ultimate strength of the connected member is restored or not, regardless of rigidity and ductility.

Classification according to ductility (Figure 20d)

- Ductility restoring connections (Ductile)
- Ductility non-restoring connections (Semi-ductile or Brittle with regard to the level of deformation)

depending on whether the ductility of the connected member is higher or lower than that of the connected member, regardless of strength and rigidity.

This classification system is more complete than the one used for steel in Eurocode 3, where the ductility aspect is neglected.

Figure 21 shows the main types of connections, generated by the relevant combination of the main behavioural properties.

The Eurocode 9 establishes a strict relationship between the type of connection according to the above classification and the calculation method used for the global analysis of the structure, as it is shown in the following Table 7.

A new contribution for the design of bolted end plate connection is given in EC9 Annex K.

The equivalent T-stub model can be used for the evaluation of the resistance of the basic components of several structural joints, i.e. in the case of beam-to-column joint (see Figure 22). Several recent theoretical and experimental analyses (Mazzolani et al., 2000b; De Matteis et al., 1999c, 2001a, 2001b, 2002b, 2003) have shown that the physical behaviour of T-stubs made of aluminium alloys is different from the one of steel, due to the hardening feature of some alloys as well as the possibility to use both aluminium and steel bolts. The intermediate failure mode 2 can show two different behaviours as shown in Figure 23. The expression of

the ultimate moments are provided for each failure mode, accordingly.

In addition to welded, bolted and riveted connections, the last part of this Chapter in Eurocode 9 is devoted to the use of adhesive bonded connections, which represents a very new issue not yet considered in the steel code.

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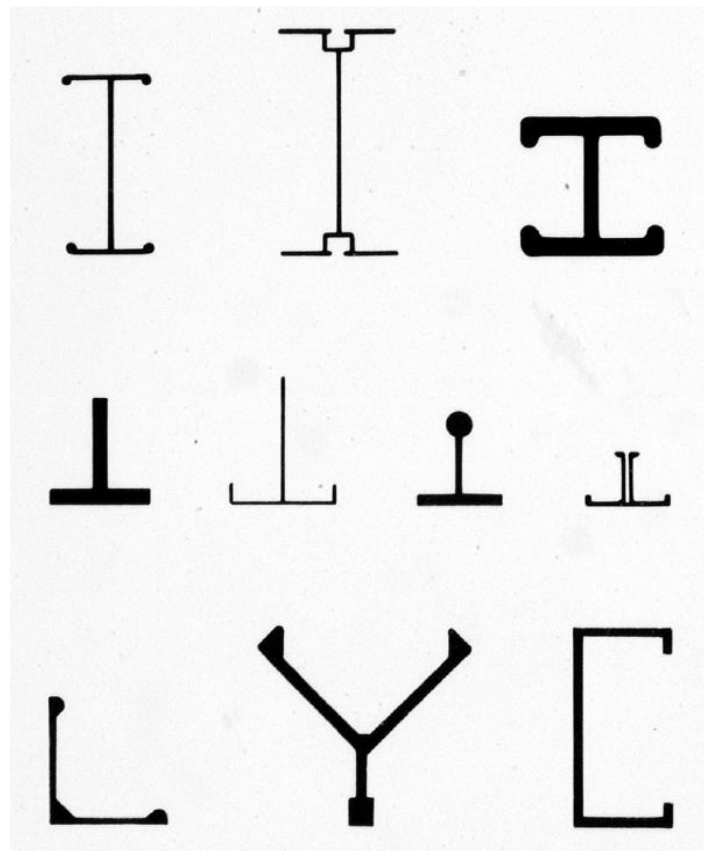
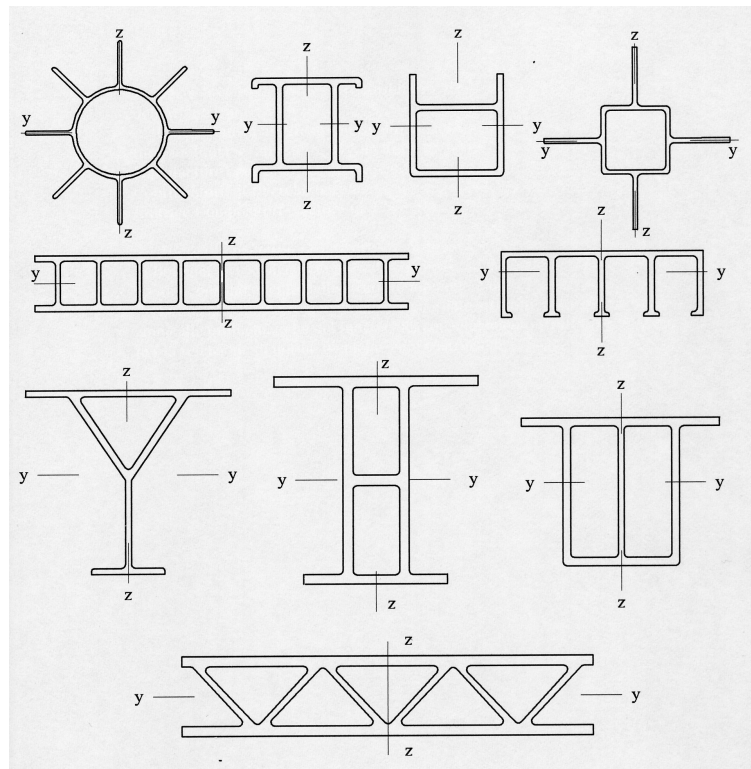


Figure 1: Typical extruded shapes.

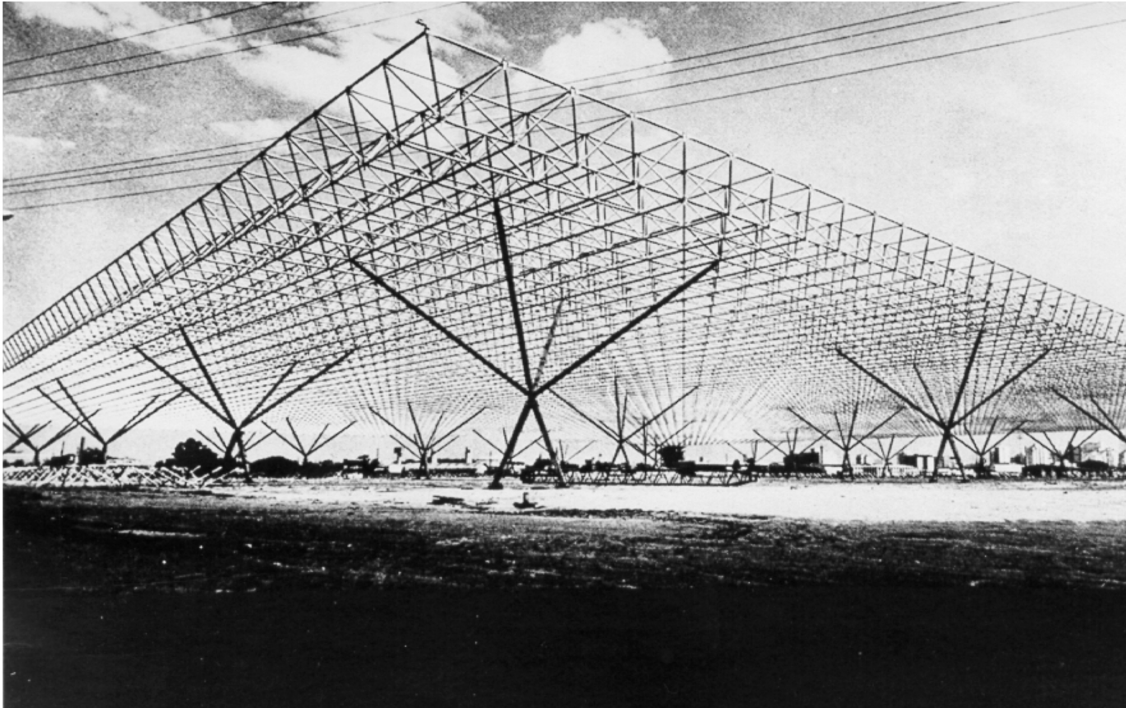


Figure 2: The roofing structure of the Interamerican Exhibition Centre of San Paolo in Brasil.

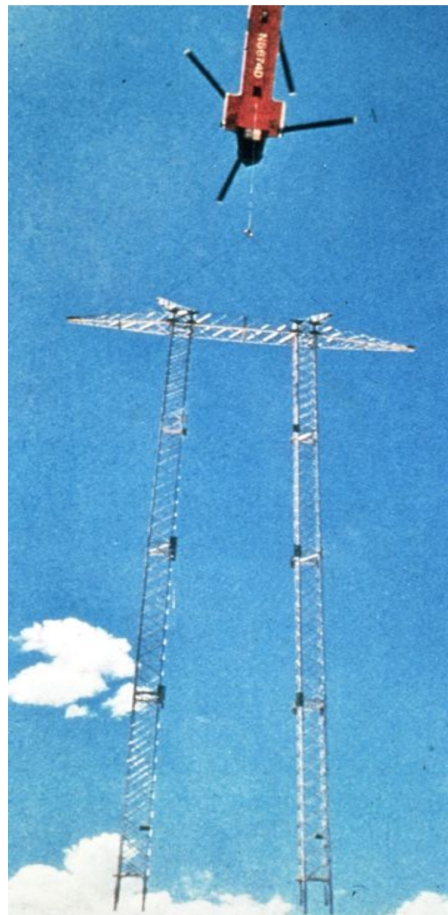


Figure 3: Transportation by helicopter of a light transmission tower.



Figure 4: Super-structures of off-shore platforms.



Figure 5: A moving foot-bridge.



Figure 6: Tower for parabolic antennas.

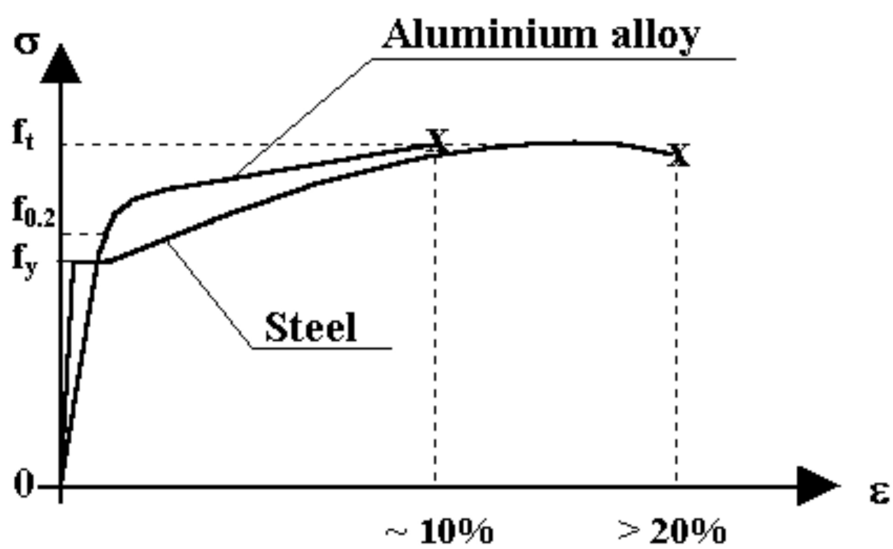


Figure 7: Comparison between typical stress-strain curves for aluminium alloys and mild steels.

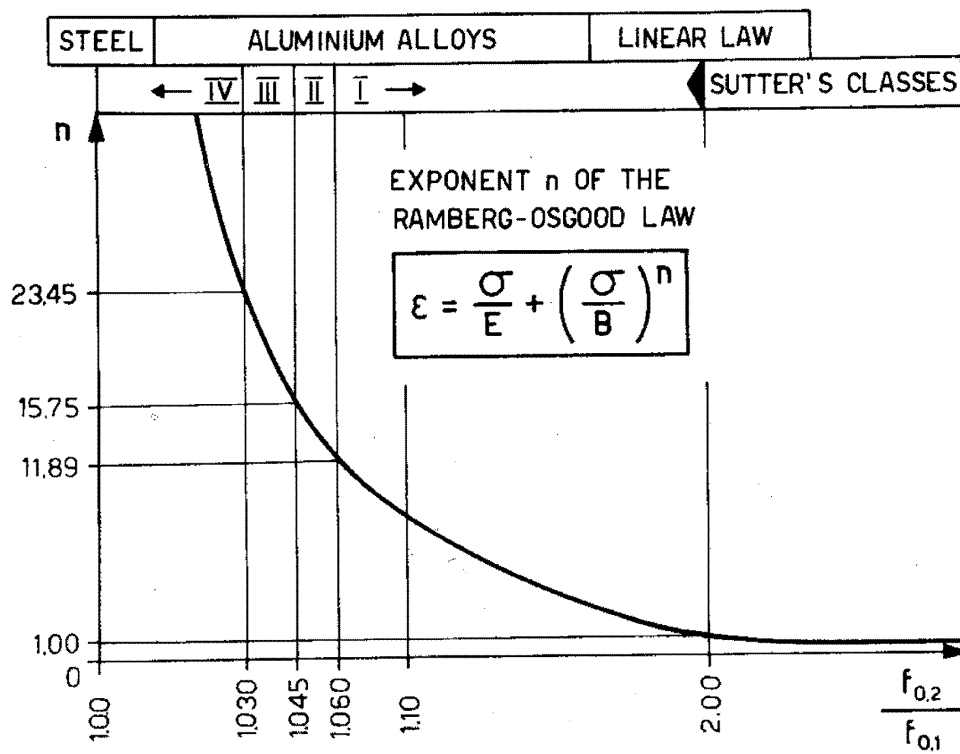


Figure 8: Relationship between the $f_{0.2}/f_{0.1}$ ratio and the exponent n of the Ramberg-Osgood law.

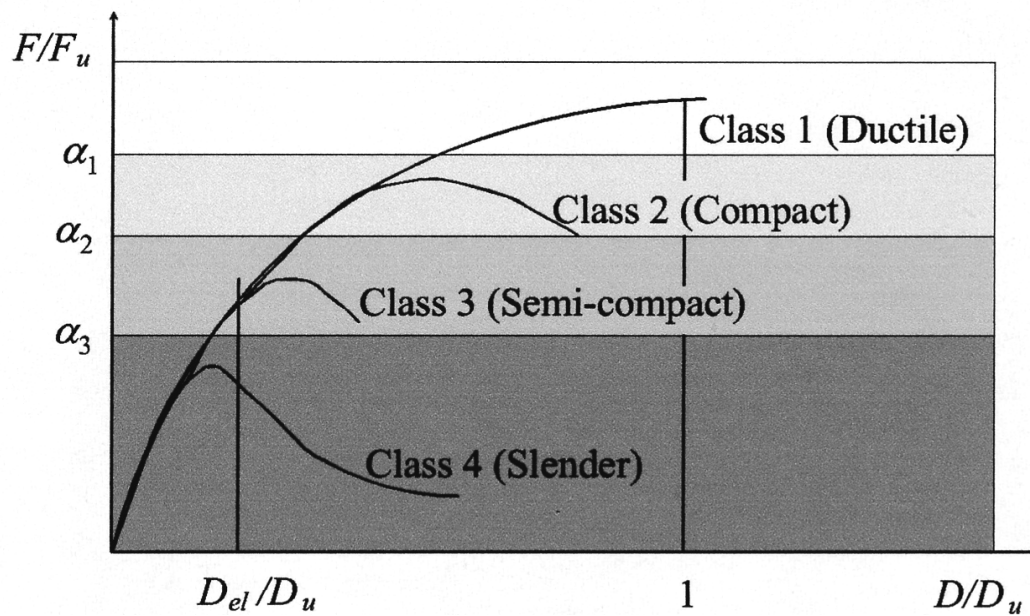


Figure 9 : Generalized non dimensional curves for cross-sectional classes.

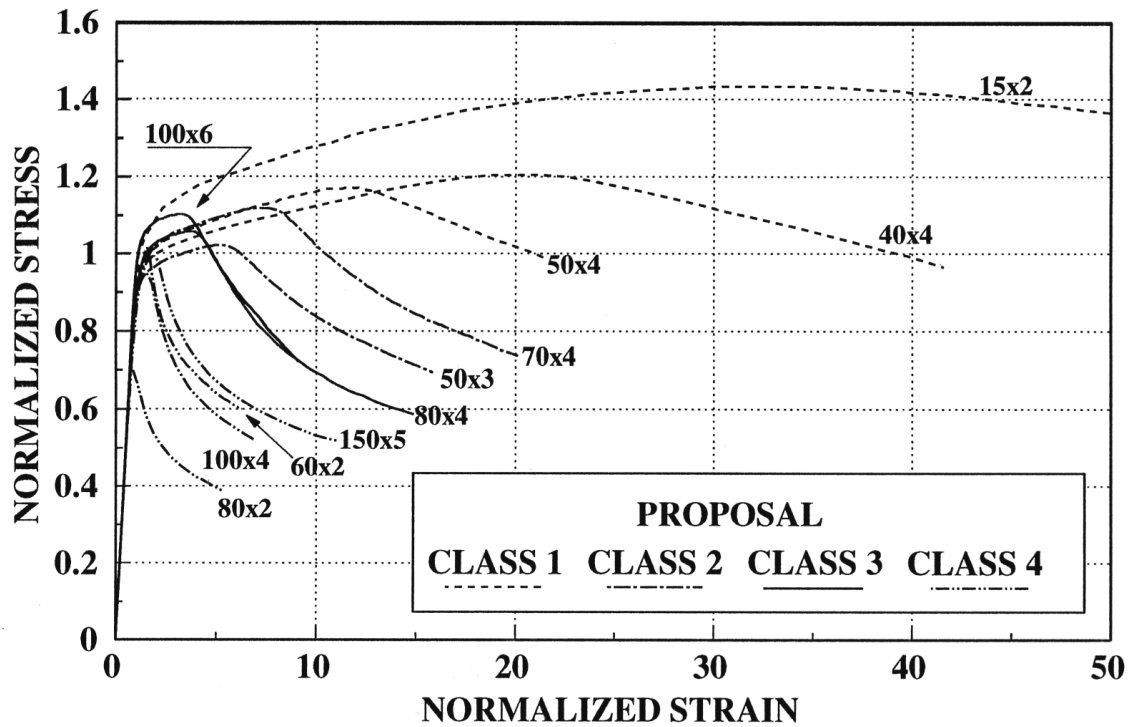


Figure 10:
Experimental normalised stress-strain curves, which identify the four behavioural classes.

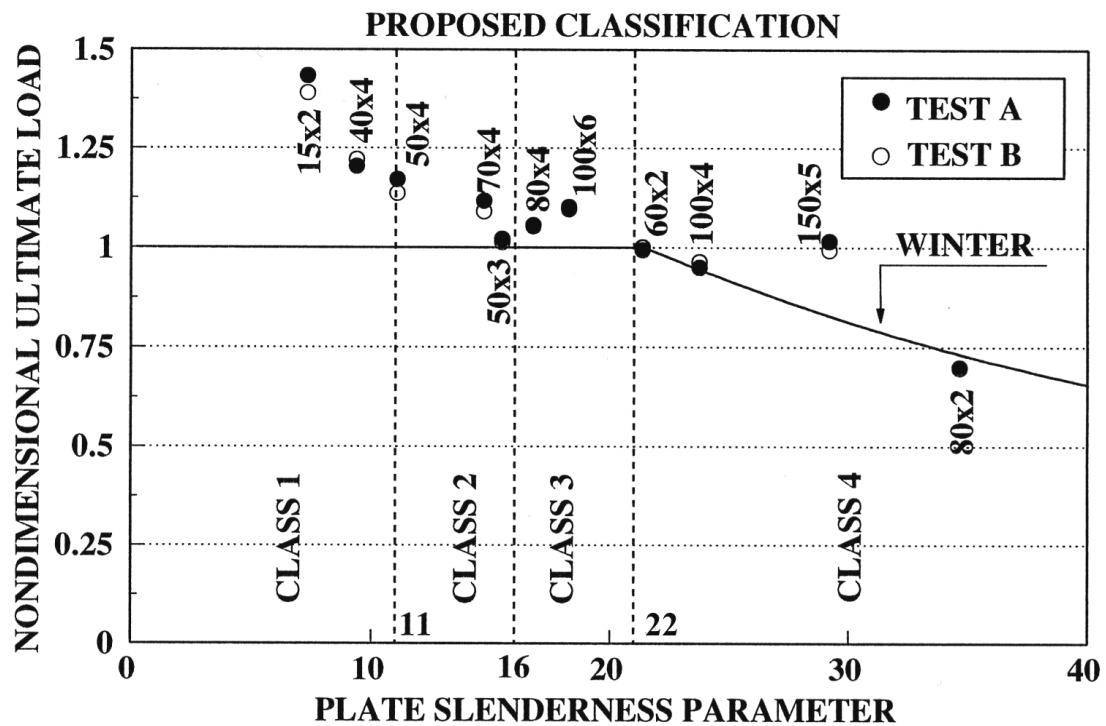


Figure 11: Boundary values of the b/t ratios for the proposed behavioural classes.

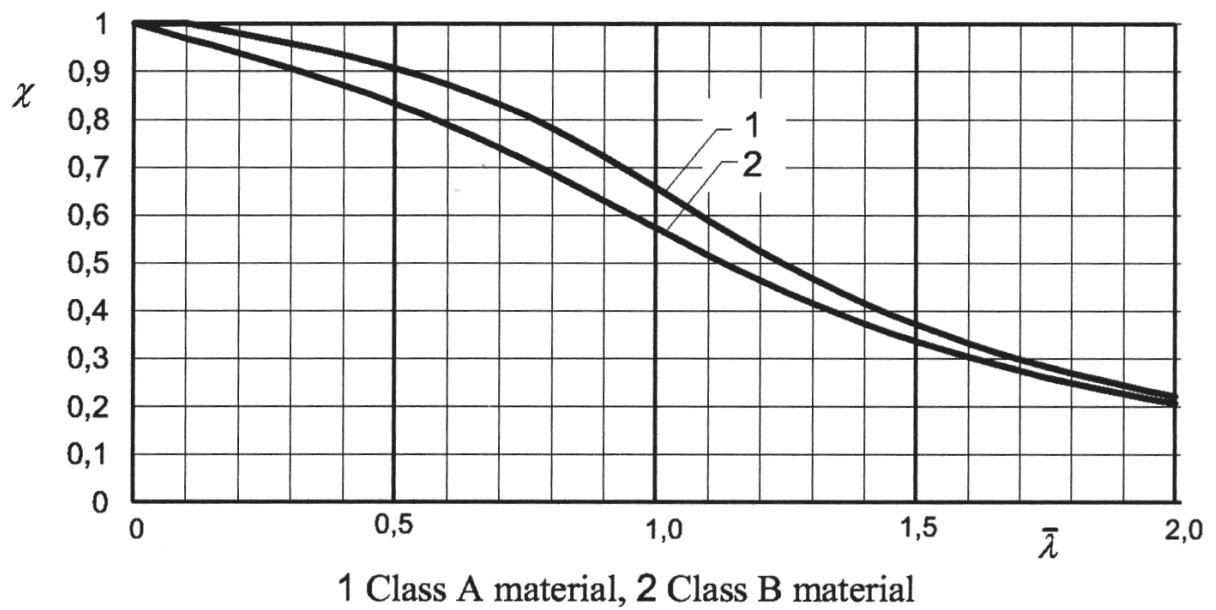


Figure 12: Column buckling curves.

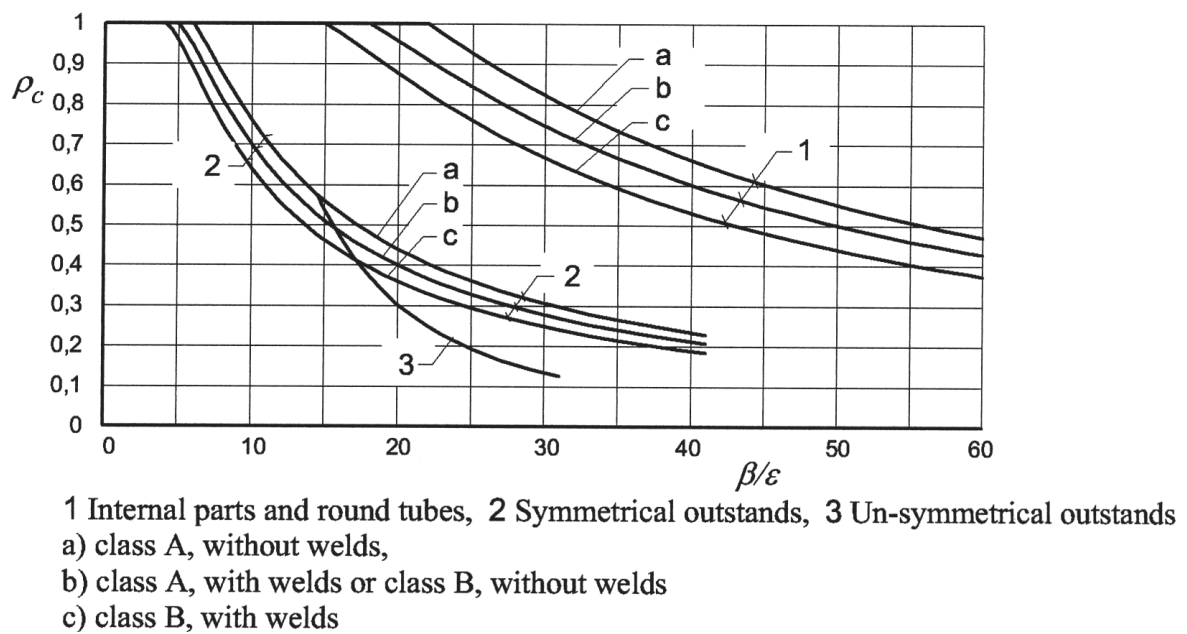


Figure 13: Buckling curves for slender sections.

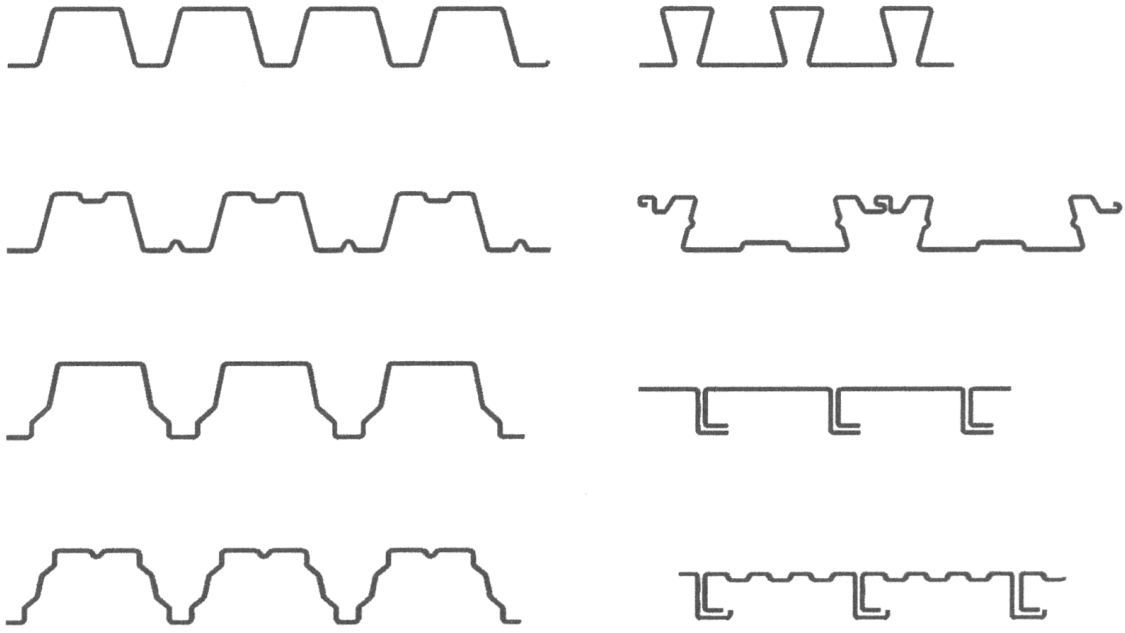


Figure 14: Trapezoidal sheeting shapes.

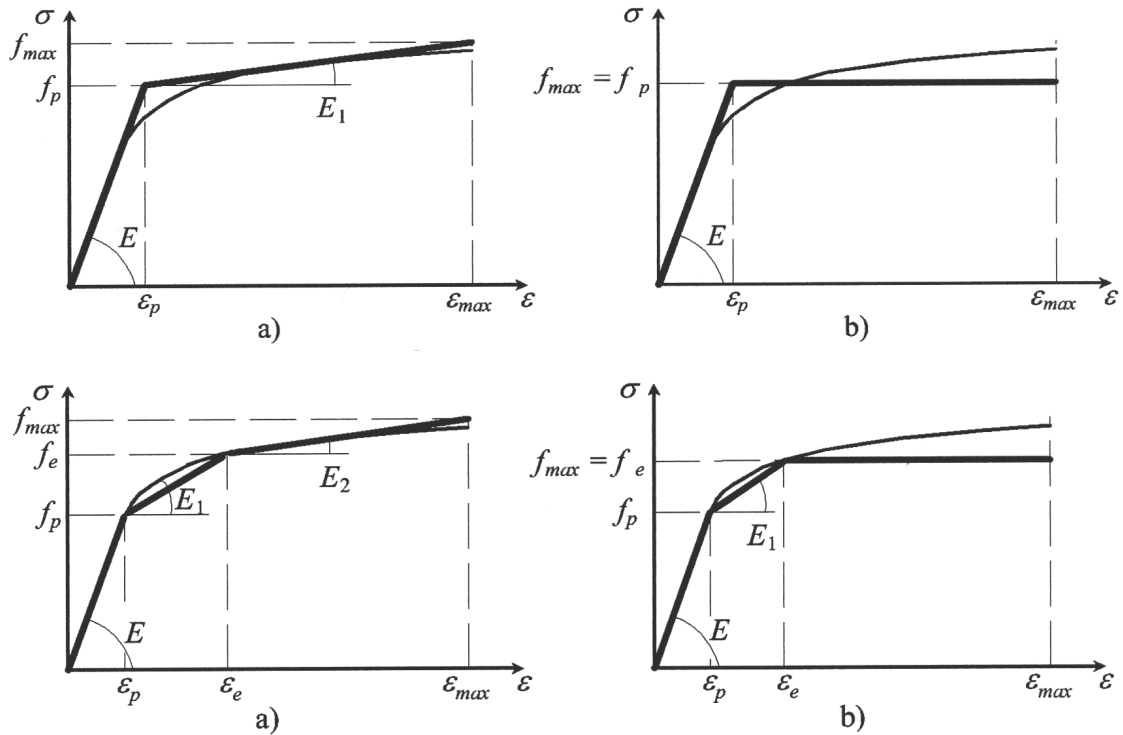


Figure 15: Simplified stress-strain models.

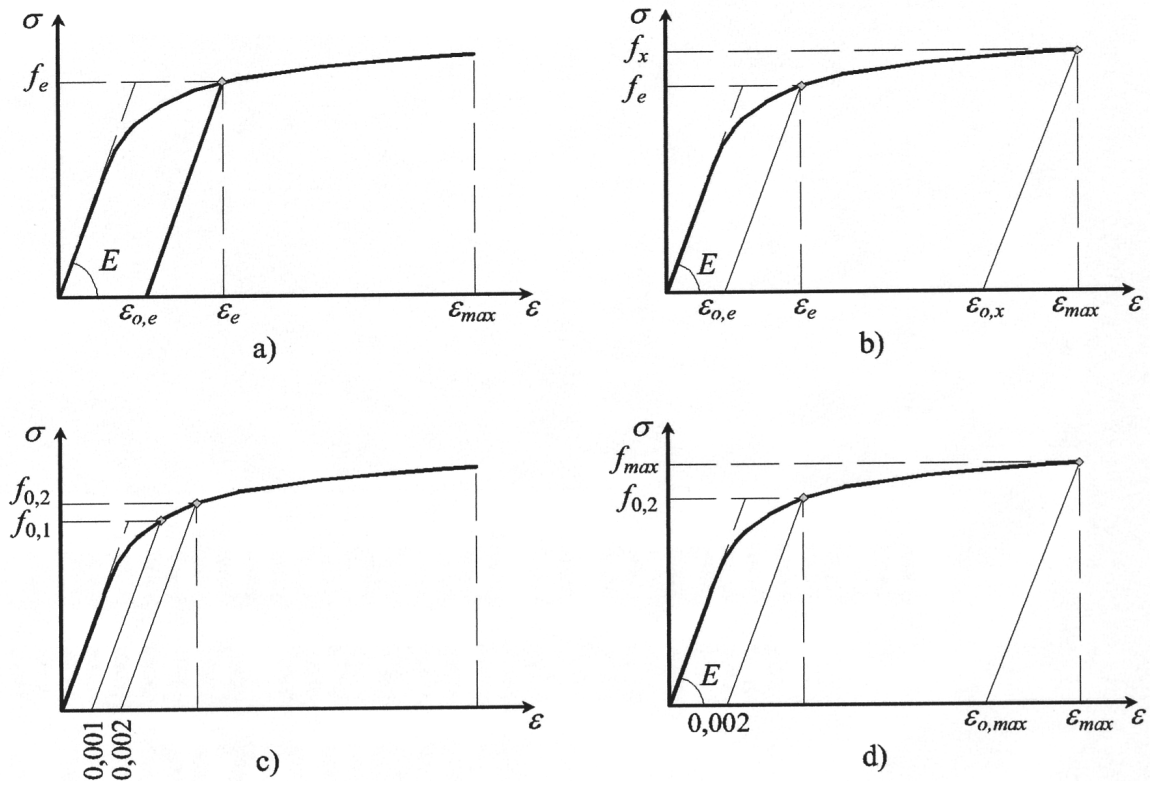


Figure 16: Continuous stress-strain models, according to the Ramberg-Osgood law.

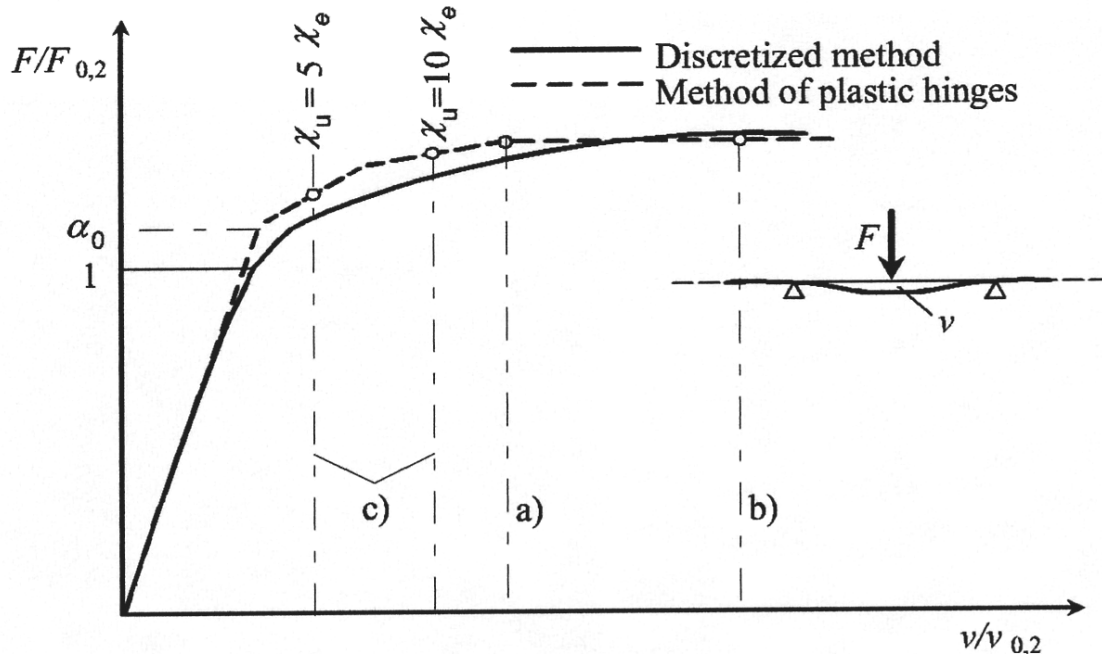


Figure 17: Load – Deflection curves : comparison between plastic hinges and discretized methods.

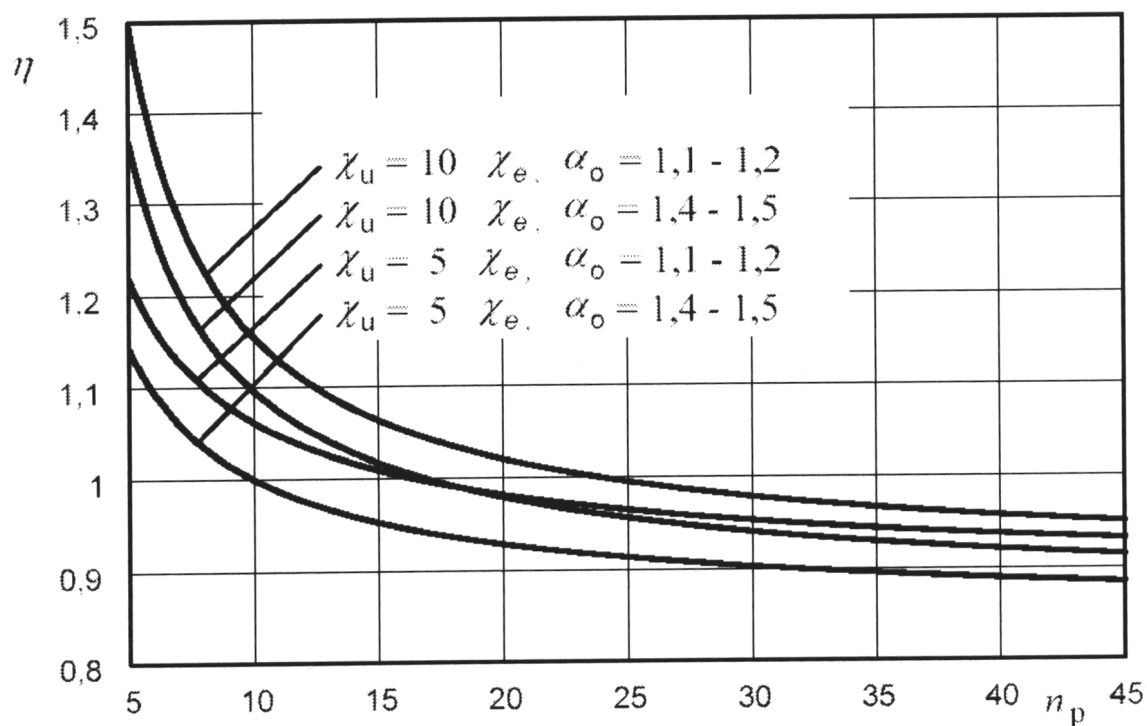


Figure 18:

The correction factor η as a function of n_p , being n_p the exponent of the Ramberg-Osgood law evaluated in plastic range.

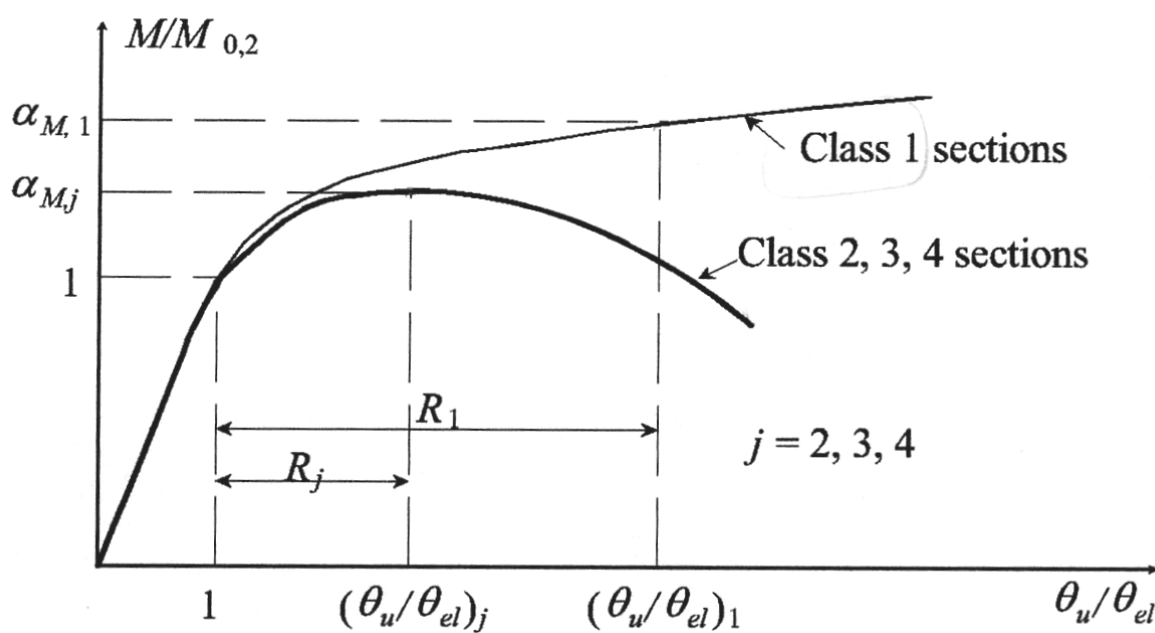
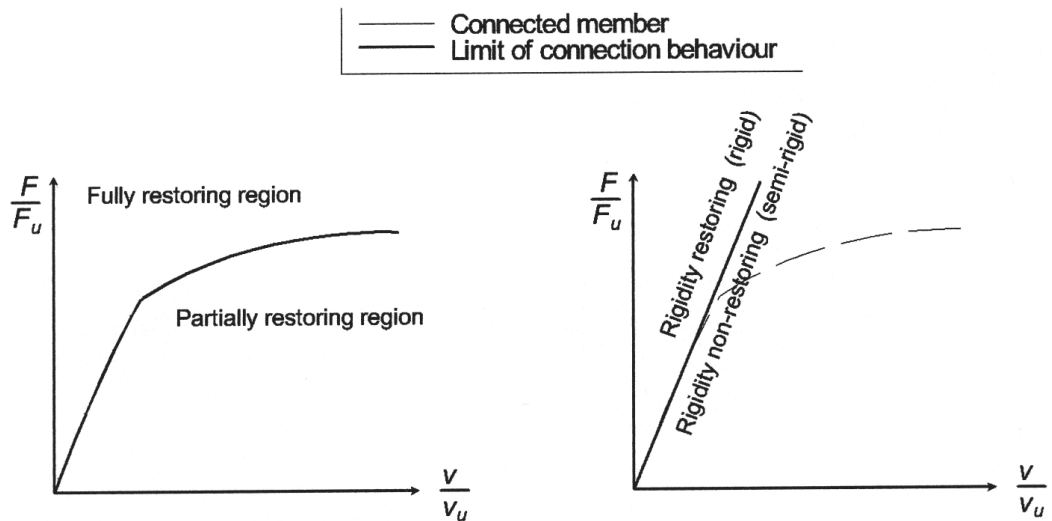
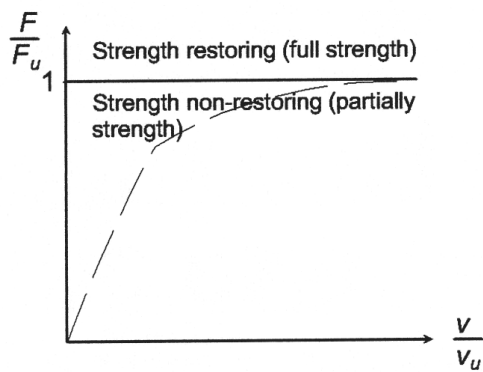


Figure 19: Definition of rotational capacity.

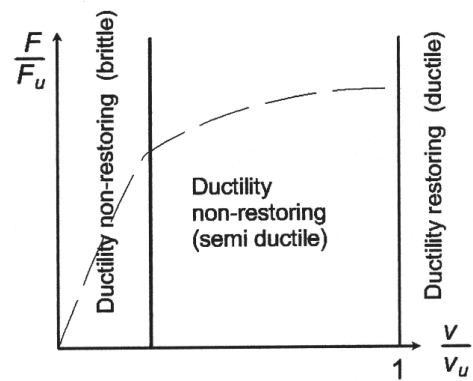


a) Classification according to member global properties restoration

b) Classification according to rigidity



c) Classification according to strength



d) Classification according to ductility

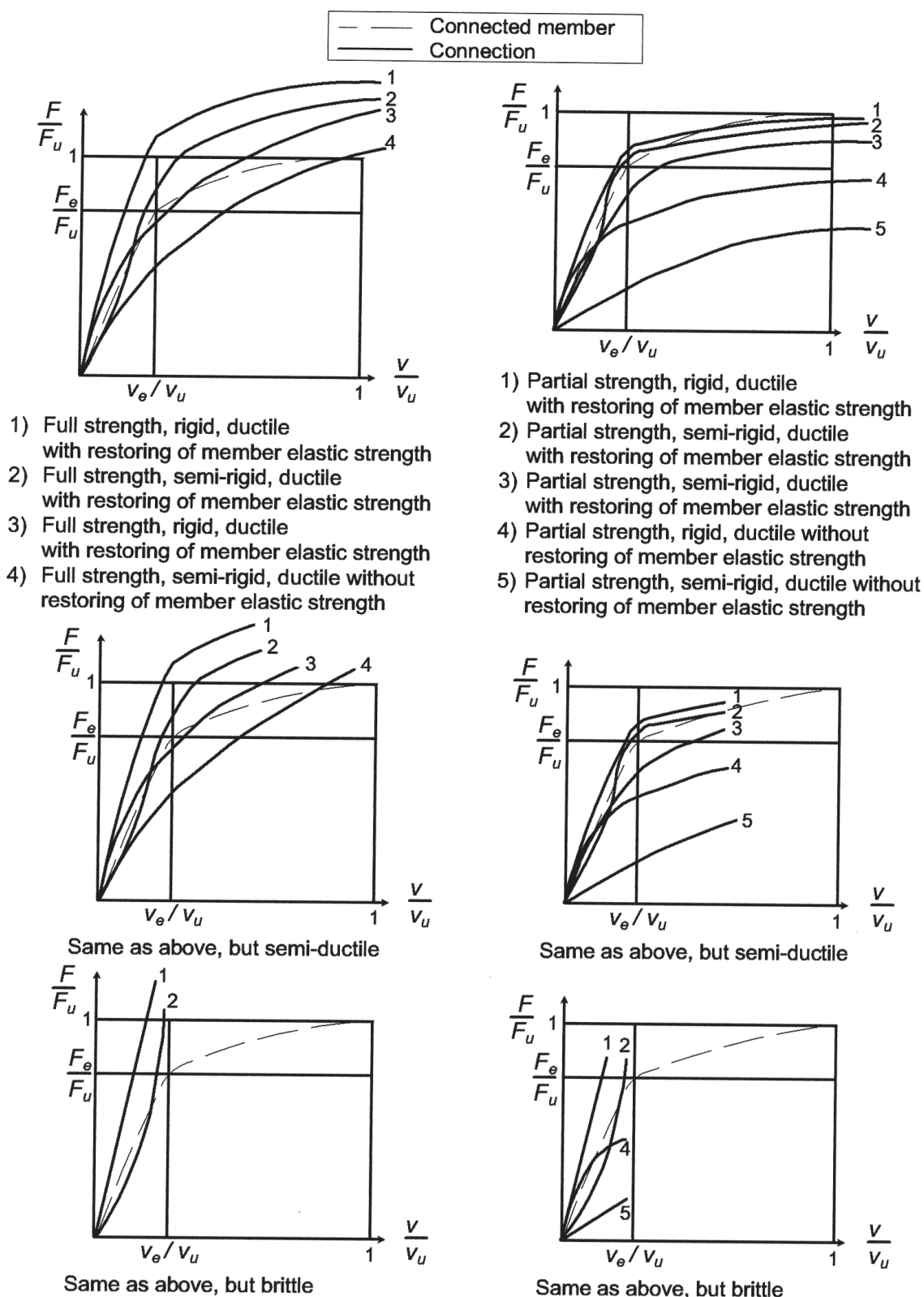


Figure 21: Main types of connections.

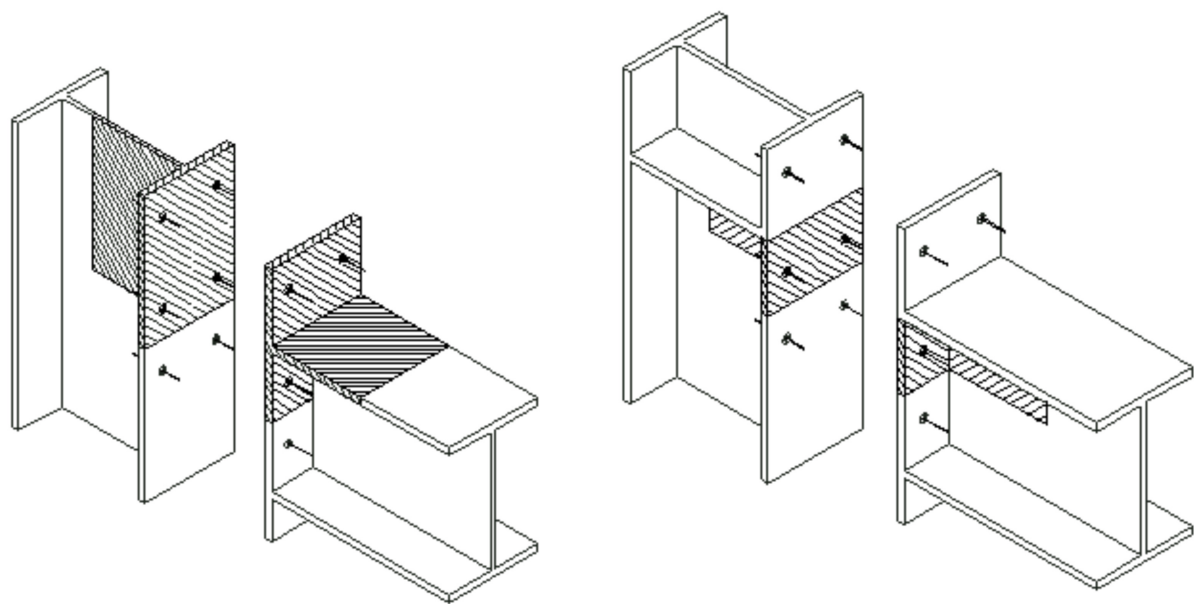


Figure 22: Equivalent T-stub model.

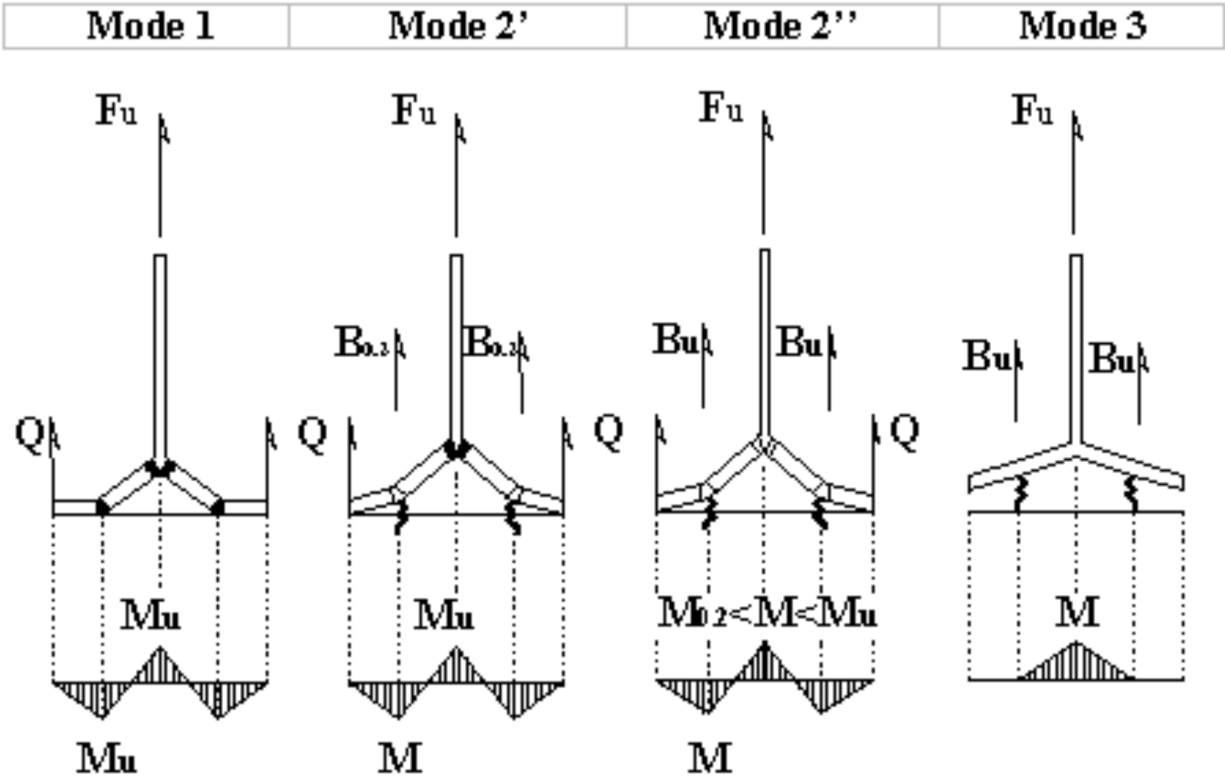


Figure 23: Different failure modes for T-stub.