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# On the Limit Behaviour of Moment Resisting Connections Under Uncertainties

Salvatore Benfratello<sup>1</sup>, Santo Vazzano<sup>1</sup>

<sup>1</sup>Department of Engineering, Università degli Studi di Palermo, Viale delle Scienze, I-90128 Palermo, Italy

Salvatore.benfratello@unipa.it

**Abstract.** Moment resisting connections are mainly designed to transfer bending moments and shear forces. Generally speaking, the design strength of a moment resisting connection can be classified as full-strength (moment capacity of the connection equal to or greater than that of the connected member) or partial-strength (the moment capacity of the connection less than that of the connected member). Similar remarks can be made regarding the stiffness defining connection rigid or semi-rigid if compared to the stiffness of the connected member. In the past, full-strength connections have been widely adopted especially in moment resisting frames and their structural performance relied on the proper behaviour of welding. However, the research following the 1994 Northridge and 1995 Kobe earthquakes demonstrated the lower than expected performance of welded connections, stimulating the onset and development of pre-qualified connections to be adopted especially in seismic areas. Among these connections the most studied ones are those belonging to the Reduced Beam Section (*RBS*) typology, being the so-called “dogbone” connection the most adopted. The dogbone presents a bending strength and a flexural stiffness lesser than the ones of the original structural member. Recently, the authors proposed a special device suitably designed to realize an innovative moment resisting connection for steel beam elements belonging to the *RBS* typology. Such a device, called Limited Resistance Plastic Device (*LRPD*), is constituted by three different portions: the central one is devoted to the onset and development of plastic deformations and presents geometrical dimensions reduced with respect to those of the original structural member; the external ones are devoted to recover the stiffness of beam-device system to that of the original structural member and present greater geometrical dimensions. This latter remark allows to affirm that, from a connectivity point of view, the stiffness of *LRPD* at the column-beam interface, is greater than the one of the original structural member. Another fundamental remark is that the structural connections are intrinsically characterized by uncertainties related either to geometrical or to material ones. Usually, the effect of uncertainties is covered by the use of safety coefficients and the analyses are performed referring only to the nominal values of the geometrical and mechanical characteristics. However, in order to perform a more complete interpretation of the mechanical behaviour of the studied connections, a non-deterministic analysis approach can be used. Aim of the paper is the characterization of the structural behaviour of the referenced connections (“dogbone” and *LRPD*) taking into account the main geometrical uncertainties and that related to the material strength by performing suitably Monte Carlo simulations and by determining the relevant *M-N* domains. Starting from the described characterization, different commercial steel profiles will be considered in order to build a series of *M-N* domains useful to quantify the safety level and the range of usability of the two different *RBS* approaches. Finally, the implemented applications will lead to demonstrate the greater reliability of *LRPD* compared to the classical dogbone.



## 1. Introduction

Frame structures represent the more adopted structural typology both in civil and industrial constructions. Among frame typology, steel moment resisting frames (MRFs) are certainly the more endorsed ones in terms of strength, weight, durability, construction speediness, material quality and flexibility also from an architectural point of view. From a mechanical point of view, MRFs are characterized by the onset of plastic hinges at the ends of beams and column bases resulting in an energy dissipation capacity greater than that available in shear wall systems and braced frames. The formation of plastic hinges is a fundamental step but brings along many remarks deeply focused on many papers available in literature (e.g. [1]-[3]).

A very important aspect to be considered in MRFs is the problem of connection performance and many papers faced this topic (e.g. [4]-[7]) starting from the extensive damages to the beam-to-column connections of the MRFs occurred during the 1994 Northridge and 1995 Kobe earthquakes. Basically, these studies resulted in the development of pre-qualified connections for use in seismic areas [6]-[7], which included the reduced beam section (*RBS*) connection.

The main idea explored in this research is that the connection failure is eliminated by the relocation of the plastic hinges by moving them from the region adjacent to the beam-column connection. In the *RBS* moment connection, parts of the beam flanges are selectively cut in the location next to the beam-column connection. The concept of *RBS* with a trapezoidal cut profile was first introduced by Plumier in 1990 [8] and Iwankiw and Carter [9]. Among all suggested cut profiles, the implementation of the curved cut profile has shown a better performance also in the case of cyclic loadings [6]. Other methods for weakening the beam section reported in literature include cutting the beam web, cutting both the beam flanges and the web concurrently, and double reduced beam section [10]-[12]. These pre-qualified connections have been also tested in extensive experimental campaigns demonstrating the large amounts of plastic hinging undergone by these connections as well as the reliable amount of hysteretic energy dissipation. However, this plastic hinging can also result in irrecoverable deformations in the beams, leading to the frame having significant residual displacements [13], which can translate into large economic losses and significant delays in the operating capability of the structure [14]. Furthermore, the rehabilitation cost of a frame equipped with *RBS* connection is prohibitive. To mitigate this issue, several low-damage alternative connections have been proposed (e.g. [15]-[17]). For a detailed description of these alternative connections see the cited references.

In some recent papers ([18]-[24]), authors proposed an innovative device devoted to realizing a new kind of moment resisting connection for steel elements referred to as Limited Resistance Rigid Perfectly Plastic Hinge (*LRPH*) which has been improved in order to accounting for a proper distributed plasticity diffusion along its length and it is renamed as Limited Resistance Rigid Plastic Device (*LRPD*) [24]. The following main ideas constitute the back-bone of *LRPD*: i) create a pre-set zone of the beam in which plastic deformations develop, leaving the remaining part of the beam in the elastic range also minimizing the rehabilitation cost; ii) design the device such that its flexural stiffness and resistance can be suitably assigned remaining independent of each other. The proposed device, from a general point of view, belongs to the *RBS* connections, but it possesses some further special features that make the device more widely usable, as it is described in the cited literature.

A very important issue in the evaluation of the mechanical behaviour of structural elements and, therefore, in that of moment connections is the presence of uncertainties related to both geometrical and material parameters and due to unavoidable technological problems inherent to production processes. This issue is usually overcome by adopting suitably selected safety coefficient, but currently it is not deeply investigated [25]-[26]. These uncertainties can lead to wrong interpretation of the structural behaviour with the consequent effects on the reliability of the structures. From the other

hand, overcome this issue simply by adopting large deterministic safety coefficients can lead to oversize the structural elements with economic loss.

Aim of the paper is to compare the mechanical performance of the last edition of *LRPD* with that of the equivalent dogbone taking into account the uncertainties related to the geometrical and mechanical parameters characterizing the devices. The mechanical performance is evaluated by determining the *M-N* domain [28] and defining a suitable safety factor.

## 2. Geometrical characteristics of the devices

In this section the geometrical characteristics of *LRPD* and dogbone are briefly summarized. The geometrical features of the *LRPD* have been in depth described in other previous paper (see, e.g., [18]-[24]). In the present paper, the last edition of the *LRPD*, represented in figure 1, is considered. The main differences with respect with the previous versions consist in the width of the inner portion flanges treated as a design variable and in the web thickness of the inner portion equal to that of the outer portions (in turn assumed equal to that of the original cross section beam element). With reference to figure 1, the following geometrical characteristics are defined:

**Table 1.** Geometrical characteristics of *LRPD*.

Characteristics	Description	Characteristics	Description
$b = b_o$	width of the outer portions	$\ell$	total length of the device
$b_i$	width of the inner portion	$t_{f,o}$	flange thickness of the outer portions
$h_o$	height of the outer portions	$t_{f,i}$	flange thickness of the inner portion
$h_i$	height of the inner portion	$t_w$	web thickness
$\ell_o$	length of the outer portions	$r_o$	welding radius between web and flanges of the outer portions
$\ell_i$	length of the inner portion	$r_i$	welding radius between web and flanges of the inner portion

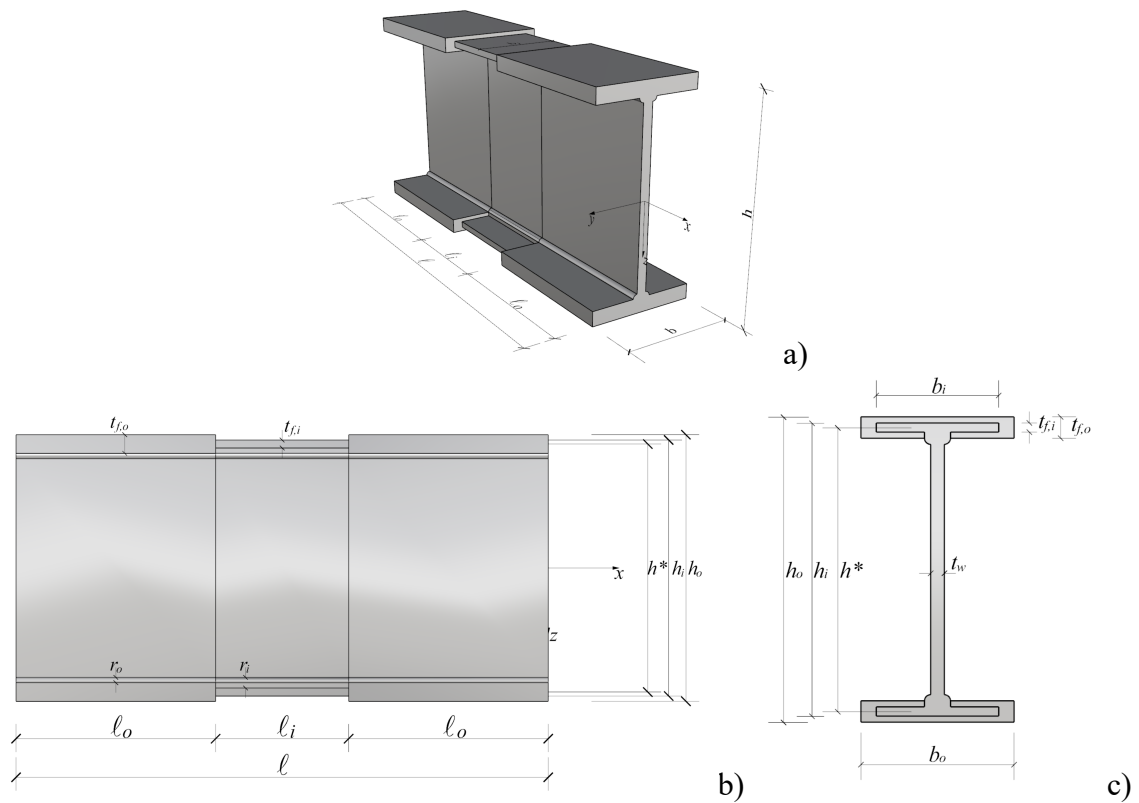
The geometrical features of the dogbone have been widely reported in many papers available in literature (see, e.g., [6],[29]). In the present paper the sketch of dogbone is reported in figure 2 and the following geometrical characteristics are defined:

**Table 2.** Geometrical characteristics of dogbone.

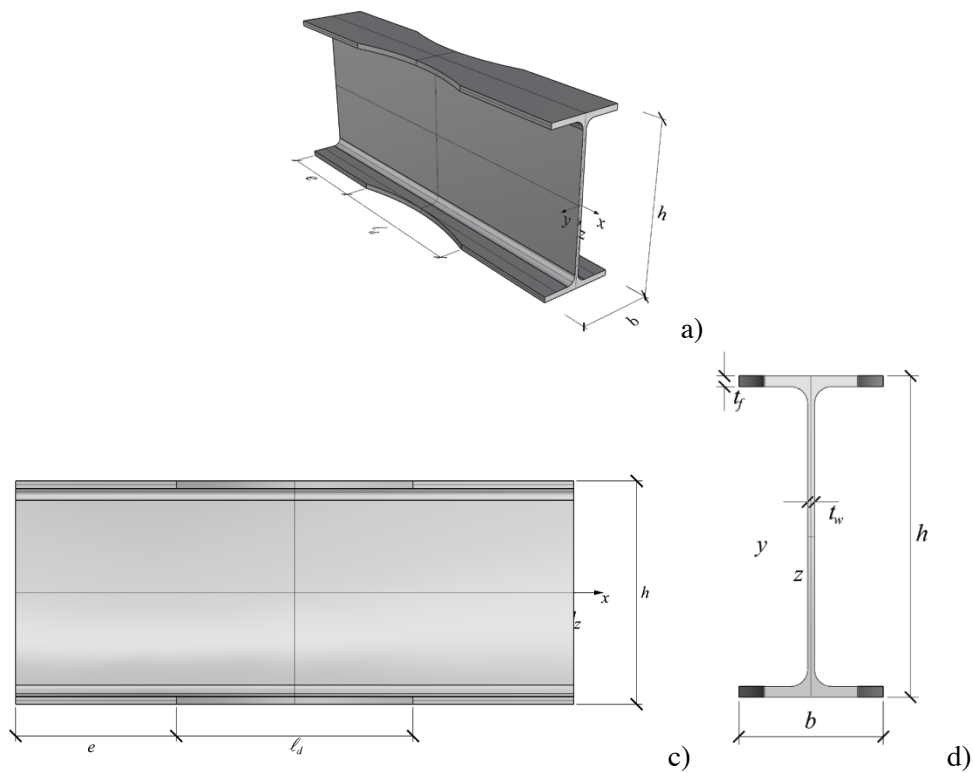
Characteristics	Description
$\ell_d$	length of the cut portion
$e$	distance between column and cut portion
$b_r$	reduced flange width

Referring to figure 2a, the parameter  $e$  indicates the distance between the initial cut section and the relevant column where the beam's end is applied on, and  $\ell_d$  measures the length of the cut portion. The shape of the cut applied on the flanges assumed in this paper is parabolic which is the common adopted one. As reported in figure 2b, the middle cut section shows a reduced flange width, called  $b_r$ , and usually indicated as percentage of the flange width of the original beam, and it represents the main parameter for the dogbone sizing.

While the dogbone technique consists in a direct intervention and modification on the beam element, the *LRPD* is thought as a device replacing a portion of the structural element, whose overall geometry is assumed to be inscribed in a parallelepiped of dimensions  $l \times b \times h$ .



**Figure 1.** Sketch of LRPD: a) 3D perspective view; b) lateral view; c) cross-sections.



**Figure 2.** Sketch of the dogbone: a) 3D perspective view; b) lateral view; c) cross-sections.

### 3. Mechanical characteristics of the devices

In this section the mechanical characteristics of *LRPD* and dogbone, useful for the development of the paper, are reported. The material composing both *LRPD* and dogbone is steel whose adopted mechanical model is elastic-perfectly plastic with elastic limit strength  $f_y$ . The strength (both elastic and plastic) of the structural element should be evaluated by taking into account the contribution of all the internal forces (i.e. axial and shear forces, bending moments and torsional one) by defining the suitable domains. In this paper, the analysis is limited to plane steel structure and, therefore the contributions of shear  $T_y$ , bending moment  $M_z$  and torsional moment  $M_x$  are neglected. Further, as it is allowed by international standards [30]-[31], the influence of the shear force  $T_z$  on the limit behaviour is neglected. As a consequence of the above remarks the strength of the structural elements is evaluated in terms of bending moment vs axial force domain (either limit elastic or limit plastic one). For the development of the paper it is useful to report the equations defining the limit plastic domain both for the *LRPD* and for dogbone. These equations can be obtained exactly or approximately by referring to the expressions available in referenced international standards. The equations for the limit plastic domain determined exactly, assuming an I-shape of the cross section, are the following ( $z_n$  being the position of the neutral axis with respect to principal reference system of the cross section):

$$0 \leq z_n \leq \frac{h}{2} - t_f - r \rightarrow \begin{cases} N = 2 t_w z_n f_y \\ M = W_{pl} f_y - t_w z_n^2 f_y \end{cases} \quad (1)$$

$$\frac{h}{2} - t_f - r \leq z_n \leq \frac{h}{2} - t_f \rightarrow \begin{cases} N = f_y \left[ A - 2bt_f - 2t_w \left( \frac{h}{2} - t_f - z_n \right) - 4A_2 \right] \\ M = f_y \left[ bt_f (h - t_f) + 2A_2 (2z_n + 2G_2) \right. \\ \left. + t_w \left( \frac{h}{2} - t_f - z_n \right) \left( \frac{h}{2} - t_f + z_n \right) \right] \end{cases} \quad (2)$$

$$\frac{h}{2} - t_f \leq z_n \leq \frac{h}{2} \rightarrow \begin{cases} N = f_y \left[ A - 2b \left( \frac{h}{2} - z_n \right) \right] \\ M = bf_y \left( \frac{h^2}{4} - z_n^2 \right) \end{cases} \quad (3)$$

In equations (2)  $A_2$ ,  $S_2$ ,  $G_2$  and  $\vartheta$  are defined by the following relationships:

$$\vartheta = 2 \arccos \left( \frac{z_n + t_f + r - h/2}{r} \right) \quad (4)$$

$$A_2 = r \left( \frac{h}{2} - t_f - z_n \right) - \frac{r^2}{4} (\vartheta - \text{sen } \vartheta) \quad (5)$$

$$S_2 = \frac{r}{2} \left( \frac{h}{2} - t_f - z_n \right)^2 - \frac{r^2}{4} (\vartheta - \text{sen } \vartheta) \left[ \frac{r^2 \text{sen } \vartheta \left( \frac{h}{2} - t_f - z_n - r \right) + 2 r^3 \text{sen} \frac{\vartheta}{2}}{\frac{3}{2} r^2 (\vartheta - \text{sen } \vartheta) + \frac{h}{2} - t_f - z_n - r} \right] \quad (6)$$

$$G_2 = S_2 / A_2 \quad (7)$$

The equations for the limit plastic domain available in the international standards, always assuming an I-shape of the cross section, are the following ( $z_n$  being the position of the neutral axis with respect to principal reference system of the cross section):

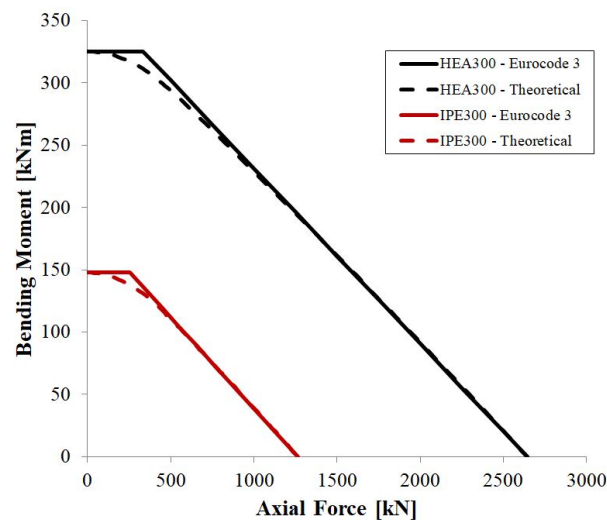
$$\left| \frac{N}{N_{pl}} + (1 - 0.5a) \frac{M}{M_{pl}} \right| = 1 \quad (8)$$

$$\left| \frac{N}{N_{pl}} - (1 - 0.5a) \frac{M}{M_{pl}} \right| = 1 \quad (9)$$

$$\left| \frac{M}{M_{pl}} \right| = 1 \quad (10)$$

being  $N_{pl} = Af_y$  the plastic limit value of the axial force,  $M_{pl} = W_{pl}f_y$  ( $W_{pl}$  being the plastic resistance modulus) the plastic limit value of the bending moment and with parameter  $a = (A - 2bt_f)/A$  subjected to  $a \leq 0.5$ .

In figure 3 both the limit elastic and limit plastic domains, in the case of an HEA300 and IPE300 profiles, obtained by the above reported equations, are sketched (for simplicity's sake only in the case of positive axial force and bending moment).



**Figure 3.** Theoretical and standard limit plastic domains for HEA300 and IPE300 profiles.

#### 4. Results and discussions

As previously remarked, the correct evaluation of the limit resistance of steel profiles in terms of M-N domain is very important when the proper uncertainties on some specific geometrical or mechanical parameters are considered. The quantities subjected to this kind of ordinary phenomenon are numerous, but for sake of brevity, and for the different impact that each of them has on the main mechanical and kinematical properties, in the present paper just some of them will be considered in the evaluation and construction of the *M-N* domains. The chosen parameters for the present paper are embedded in the vector:

$$\mathbf{v}^T = |h \quad b \quad t_f \quad t_w \quad r \quad f_y| \quad (11)$$

The geometrical parameters reported in equation (11) usually depends on site or local-fabric manufacturing (such as all the geometric features which are subjected to cut/other alteration) but, in the framework of qualified production, their variation is governed by relevant standard [32-33]; from a mechanical point of view also the limit elastic strength of material  $f_y$  is variable and it depends on big-scale production. In all the examined cases (i.e. the dogbone one, the inner and outer cross section of the *LRPD* device and the relevant starting commercial steel profile) the type of cross section considered is always an I-shaped one. Therefore, in order to perform numerical application and to obtain a synthetic representation, the following matrix can be defined, containing the corresponding vector in equation (11) for each examined case:

$$\mathbf{V} = \begin{bmatrix} \tilde{v}^{db} \\ \tilde{v}^0 \\ \tilde{v}^i \\ \tilde{v}^p \end{bmatrix} = \begin{bmatrix} h & b_i & t_f & t_w & r & f_y \\ h_0 & b & t_{f,0} & t_w & r_0 & f_y \\ h_i & b & t_{f,i} & t_w & r_i & f_y \\ h & b & t_{f,p} & t_{w,p} & r & f_y \end{bmatrix} \quad (12)$$

where  $\mathbf{v}^{db}$  represents the vector related to the dogbone,  $\mathbf{v}^0$  and  $\mathbf{v}^i$  the analogous vectors related to the outer and the inner portions of the relevant *LRPD*, and  $\mathbf{v}^p$  the one related to the standard profile.

From a numerical point of view the matrix  $\mathbf{V}$  is completely defined when the probabilistic characterization of the uncertainties is performed. As it is usually accepted, the probability distribution function for the variables considered in this paper is the normal one, which requires only the mean and the standard deviation in order to be fully defined. Further, from a probabilistic point of view the random variables are assumed to be statistically independent each other. In this paper a Monte Carlo simulation has been performed considering a sufficient large number of random values of the values reported in equation (12).

In order to compare the difference safety level of the dogbone with respect to the *LRPD* device, each of them must be designed and deterministically described. The first step is to choose a percentage of reduction of the base of the dogbone. This will let the beam to experience the desired reduction of its limit resistance. The level of reduction adopted in this application is 40%, which is a common reduction level for common use of this technology. To perform a correct comparison of the mechanical behaviour of *LRPD* and dogbone, the reduction resistance of the *LRPD* must be equal to that of the dogbone, that is

$$W_{pl,dogbone} = W_{pl,LRPD} \quad (13)$$

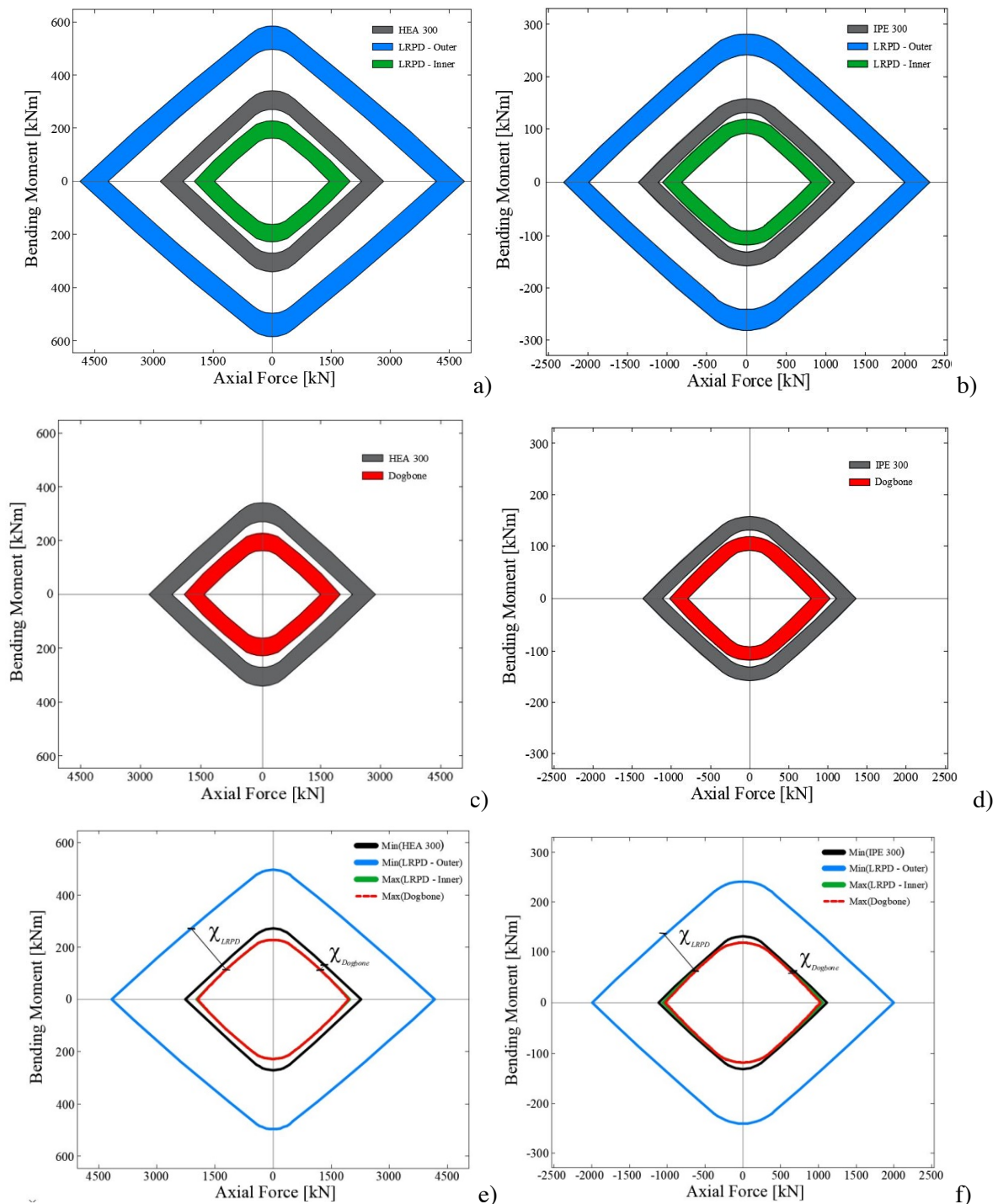
The Monte Carlo simulation has been performed considering 1,000,000 samples and characterizing the mean vector considering the nominal values of the parameters and the variance vector as follows [32]:

$$\tilde{\sigma}^2 = |0.09 \quad 0.09 \quad 0.04 \quad 0.01 \quad 0.64 \quad 0.01| \quad (14)$$

The above-described simulation has been performed for two different cases: the first one considers an HEA300 profile and the second one an IPE300 profile. For each generated sample the corresponding point of the *M-N* domain has been identified and the consequent graphs can be drawn in order to compare their mechanical performance (figure 4).

The performed applications and the obtained *M-N* domains allow to define a new kind of safety coefficient for the dogbone, defined as the distance between the inner border of the relevant profile domain and the outer border of the dogbone domain. Similarly, for the *LRPD*, the safety coefficient can be defined as the distance between the inner border of the outer portion domain and the outer border of the inner portion domain. These safety coefficients are graphically indicated in figures 4e and 4f for HEA300 and IPE300 profiles, respectively. As it can be easily deduced, the safety coefficient of *LRPD* is higher than that of the dogbone.





**Figure 4.** Comparison of  $M-N$  domains: a) HEA300 vs  $LRPD$ ; b) IPE300 vs  $LRPD$ ; c) HEA300 vs dogbone; d) IPE300 vs dogbone; e) safety coefficient for HEA300; f) safety coefficient for IPE300.

### 5. Conclusions

In the present paper the evaluation of the limit plastic domains of two moment connections has been performed taking into account the probabilistic character of the fundamental parameters governing the geometrical and mechanical behaviour of the cross-section (assumed as I-shape). The obtained results allowed the definition of a new kind of safety coefficient to evaluate the mechanical performance of

the connection under examination. This safety coefficient is defined as the distance between the outer border of the  $M-N$  domain of the weak portion of the connection and the inner border of the  $M-N$  domain of the strong portion of the connection. The obtained results allow to affirm that the *LRPD* possesses a safety coefficient higher than that of the dogbone.

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