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Iterative Optimal Design of Special Moment Resisting Devices for Steel Frames

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Iterative Optimal Design of Special Moment Resisting Devices for Steel Frames

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Abstract. The present paper proposes an iterative procedure devoted to reaching the optimal design of an innovative, recently proposed, moment resisting device. This special device, called Limited Resistance Plastic Device (*LRPD*), can be utilized, as an example, to equip a steel frame when it is required that the frame must be designed to substitute a masonry panel, i.e., it must be characterized by a structural behaviour as close as possible to the one of the replaced masonry wall. This purpose can be reached by designing the relevant frame imposing appropriate constraints on the elastic stiffness and on the limit resistance. The result can be obtained just by ensuring that the elastic stiffness and the limit resistance be independent of each other. To this aim it is necessary to suitably equip the steel frame by the previously cited *LRPD*. In particular, these moment resisting connections ensure that in a prefixed portion of the given beam element, the limit bending moment reduces without any variation of the global elastic stiffness. In order to reach this goal, the *LRPD* is substantially constituted by an inner portion, devoted to exhibit the desired reduced limit bending strength and to receive the plastic deformations, and two outer portions, devoted to guarantee the invariance of the elastic bending stiffness. The proposed iterative procedure allows to design a device respecting all the required features avoiding the presence of any dangerous local instability phenomenon. To this aim, the design will contain appropriate constraints ensuring that the device cross sections appertain to class 1 or class 2 I-cross section, as prescribed in the more recent standard codes. Some examples, validated by 3D solid tetrahedral elements analysis in ABAQUS environment, prove the good reliability of the proposed procedure and show the easy applicability of the computational approach.

1. Introduction

In some recent papers [1]-[7], the authors proposed a special device suitably designed to realizing an innovative moment resisting connection for steel beam elements. Such a device, called Limited Resistance Plastic Device (*LRPD*), can be considered as belonging to the wider field of the "reduced beam section" connections (*RBS*) (see, e.g., [8]-[16]) and consists of a steel element (figure 1) constituted by three subsequent portions. This device is preferably inserted to join columns and beams. The following two main ideas substantially constitute the founding basis of *LRPD*:

i) create a suitably chosen portion of the beam element where plastic deformations must develop, leaving the remaining part of the beam element in the purely elastic range;

ii) design the optimal device in such a way that its flexural stiffness and its limit resistance can be suitably assigned, being independent of each other.
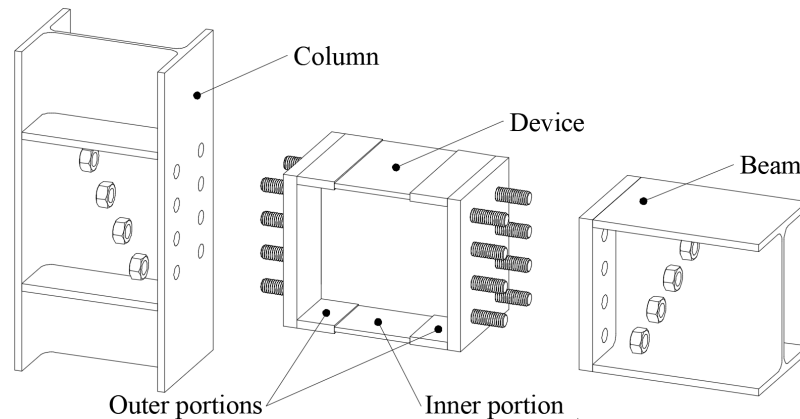

Figure 1. Typical *LRPD* connection.

The possibility of equipping a steel frame by the described innovative device permits to the designer to address the structural response of the relevant frame in which they are inserted in an appropriately chosen direction. In particular, by exploiting the fundamental feature of the device, i.e. the one that ensure that the device can show stiffness and strength independent of each other, a steel frame which is characterized by prefixed capacity curves can be easily designed [1]. This special feature is particularly important in applied engineering especially, as an example, in the case of a frame which must be designed to substitute a masonry panel, i.e., a steel frame which must exhibit a structural behaviour as close as possible to the replaced masonry wall.

In order to ensure the effectiveness of these devices, it is necessary that a complete plastic deformation field can occur and that this desired behaviour avoids the presence of any dangerous local instability phenomenon. Such a good behaviour can be ensured by designing the device dimensions in such a way that the smaller (inner) cross section, i.e. the one where the complete plastic deformation field is expected, possesses the characteristics of a class 1 or class 2 I-cross section, as prescribed in the more recent standard codes [17]-[19].

In the present paper, a simple computational iterative procedure is proposed devoted to obtain a reliable sub-optimal design of the devices to be located in suitably chosen cross sections of the steel frame obtaining the required elastic stiffness behaviour as well as the desired limit resistance.

The computational iterative procedure consists of the following main steps:
1. the reduced limit bending moment value (or, analogously, the plastic modulus of the cross inner section devoted to suffering the full field of plastic deformation) is suitably assigned to equip the frame with the desired behaviour;
2. the length of the inner portion is fixed equal to 0.5 of the original cross section depth (see, e.g., [1], [4]);
3. an appropriate range of values for the internal lever arm of the inner cross section of the device is fixed and a suitably chosen finite number of computational analysis steps is utilized;
4. for each computational step the thickness of the flange of the inner portion is calculated and the related ductility cross section class is evaluated;
5. in correspondence of the steps in which the inner cross section does not appertain to class 1 or class 2, keeping fixed the internal lever arm of the inner cross section, the width of the flange is iteratively reduced (for fixed reduction percentage) and consequently the thickness of the same

flange increases till ensuring the appertaining at least to class 2 and, simultaneously, respecting the assigned limit bending moment value;

6. the flange thickness and the length of the outer portions are computed by imposing the same internal lever arm for all the portions of the device and the unchanging of the original elastic stiffness, respectively;

7. the minimum volume of the device among all the admissible designs is chosen as the optimal solution.

Some numerical examples are effected in order to check the good reliability of the proposed computational iterative procedure, which is related with a very low computational effort. In particular, reference is made to an IPE300 profile and to an HEA300 profile. For both the chosen original profiles two different reduction percentages are considered for the limit bending moment value. In all the considered cases, the procedure has shown good stability features and the obtained results provided devices respecting all the imposed constraints, as it has been verified by comparing the elastic stiffness of the devices and the one of the original profiles and plotting the relevant elastic and plastic domains of the optimal devices. Finally, the expected elastic and limit behaviour of the devices have been verified by modelling by 3D solid tetrahedral elements in ABAQUS environment the relevant structures.

2. Geometry and mechanical characteristics of the device

The geometric features of the *LRPD* have been in depth described in other previous paper (see, e.g., [1]-[7]). In the present paper, a new version of the *LRPD* is proposed and it is represented in figure 2, where, differently by the previous version, the width of the inner portion flanges is treated as a design variable, and it can be lower of the width of the outer portions (imposed equal to the one of the original cross section beam element).
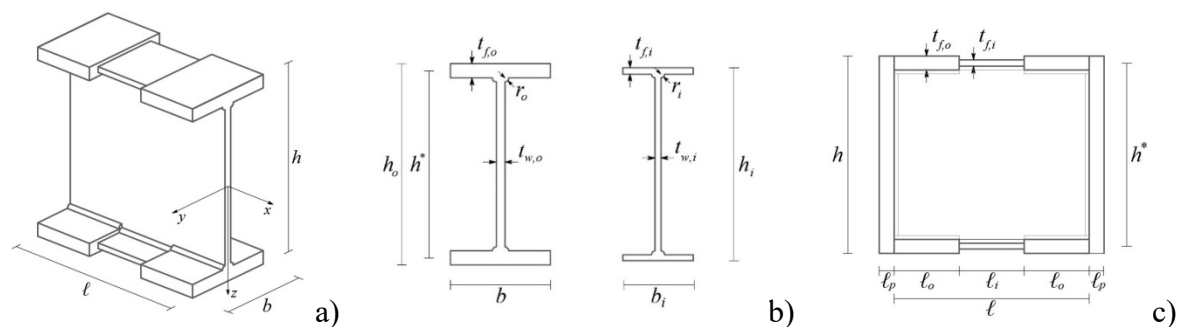

Figure 2. Sketch of the device: a) illustrative axonometric view; b) cross-sections with the relevant geometric parameters; c) lateral view.

The need of involving the width of the flanges of the inner portion among the design variables is related to the need of ensuring that the inner cross section can receive an appropriate field of plastic deformation avoiding instability, i.e., ensuring that it appertains to class 1 or class 2 I-cross section, as prescribed in the most recent standard codes.

The mechanical behaviour of the *LRPD*, for the sake of simplicity, will be referred just to plane systems and the influence of the shear force on the limit behaviour will be neglected. By assuming an elastic-perfectly plastic material behaviour, each cross section is characterized by an elastic domain described by the following dimensionless conditions:

$$\left| \frac{N}{N_{el}} + \frac{M}{M_{el}} \right| = 1 \tag{1}$$

$$\left| \frac{N}{N_{el}} - \frac{M}{M_{el}} \right| = 1 \tag{2}$$

being $N_{el} = A f_y$ the elastic limit value of the axial force and $M_{el} = W_{el} f_y$ the elastic limit value of the bending moment, with f_y the material yield stress. On the other hand, the plastic domain can be described by the following dimensionless conditions:

$$\left| \frac{N}{N_{pl}} + (1 - 0.5a) \frac{M}{M_{pl}} \right| = 1 \tag{3}$$

$$\left| \frac{N}{N_{pl}} - (1 - 0.5a) \frac{M}{M_{pl}} \right| = 1 \tag{4}$$

$$\left| \frac{M}{M_{pl}} \right| = 1 \tag{5}$$

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

As previously stated, the portion devoted to reach its limit bending moment value and to suffer the desired plastic curvature field is the inner one, so that the reference resistance domain for the inner cross section is described by the following dimensionless conditions:

$$\left| \frac{N_a}{N_{pl,i}} + (1 - 0.5a_i) \frac{\alpha W_{pl,p}}{W_{pl,i}} \right| = 1 \tag{6}$$

$$\left| \frac{N_a}{N_{pl,i}} - (1 - 0.5a_i) \frac{\alpha W_{pl,p}}{W_{pl,i}} \right| = 1 \tag{7}$$

$$\left| \frac{\alpha W_{pl,p}}{W_{pl,i}} \right| = 1 \tag{8}$$

being N_a the assigned acting axial force, $N_{pl,i} = A_i f_y$ the plastic limit value of the axial force related to the inner portion, $W_{pl,p}$ and $W_{pl,i}$ the plastic modulus of the original beam element profile and the plastic modulus of the cross section of the inner portion of the device, α the coefficient defining the reduction percentage of the limit bending strength and $a_i = (A_i - 2b_i t_{f,i})/A_i$ always subjected to the constraint $a_i \leq 0.5$

Finally, respecting the requirement that any variation of the elastic stiffness with respect of the original beam behaviour must be avoided, the following constraint must be satisfied (see, e.g., [1], [7]):

$$\frac{\ell_i}{\ell_o} = 2 \frac{I_i}{I_o} \left(\frac{I_o - I_p}{I_p - I_i} \right) \tag{9}$$

being ℓ_i the length of the inner portion and ℓ_o the common length of the outer portions, while I_i, I_o and I_p are the moment of inertia of the cross sections of the inner portion, of the outer portions and of original beam profile, respectively.

3. Optimization iterative procedure
As previously remarked, *LRPD* is a device to join with an assigned steel I-cross section beam element and devoted to produce a local reduction of bending strength without any variation in elastic stiffness.

An optimal design of the device can be reached by utilizing an appropriate computational iterative procedure. The proposed procedure is constituted by the following steps:

1. choose a standard I-cross section, select the appropriate material (e.g., HEB240, steel type S235) and evaluate the related limit bending moment value $M_{pl,p}$;
2. assign the suitable parameter α which reduces the limit bending moment value;
3. for the device: impose

$$\ell_i = 0.5h_p \tag{10}$$

$$t_w = t_{w,i} = t_{w,o} = t_{w,p} \tag{11}$$

$$h_d^* = h_i^* = h_o^* \tag{12}$$

being h_p and $t_{w,p}$ the depth and the web thickness of the selected standard profile, and h_d^* the common internal lever arm of the I-cross sections constituting inner and outer portions of the device;

4. assign an appropriate range of values for the internal lever arm of the device $\beta h_p^* \leq h_d^* \leq h_p^*$, with

$$\beta = \left(h_p - 40\right)/h_p^* \tag{13}$$

being h_p^* the internal lever arm of the selected standard profile;

5. assign a finite number of steps

$$N_{h^*} = (1 - \beta)/\gamma \tag{14}$$

with γ appropriate scalar, and for each step $(1,2,\dots,N_{h^*})$, evaluate the thickness of the flanges of the inner portion by imposing

$$W_{pl,i} = \alpha\, M_{pl,p}/f_y \tag{15}$$

that can be usefully written in the following simplified form (just function of $t_{f,i}$)

$$t_{f,i}^2 + 2\left(\frac{2b_i h_d^*}{t_w} - h_d^* - \frac{\pi r_o^2}{t_w}\right)t_{f,i} + h_d^{*\,2} + \frac{2\pi r_o^2}{t_w}\left(h_d^* - \frac{8r_o}{3\pi}\right) - \frac{4\alpha}{t_w}\frac{M_{pl,p}}{f_y} = 0 \tag{16}$$

6. check the class of ductility related to the defined inner I-cross section by the constraint

$$\frac{c}{t_{f,i}} \leq 10\varepsilon \tag{17}$$

with $c = \frac{b - t_w - 2r}{2}$ and $\varepsilon = \sqrt{\frac{235}{f_y}}$;

7. for the typical step in which the previous check provides I-cross sections not appertaining to class 1 or class 2, always for the same fixed value of the internal lever arm, the width of the flanges is reduced by

$$b_n = \frac{100 - n}{100}b \quad (n = 1,2,\dots) \tag{18}$$

and a new enlarged value of the inner portion flange thickness is calculated by equation (16) in such a way the limit bending moment be unaltered till the cross section respects at least the features of the class 2 of ductility;

8. for each step the thickness of the outer portions is evaluated

$$t_{f,o} = h_p - h_d^* \tag{19}$$

and, consequently, the length of the same portions are calculated by imposing the invariance of the global elastic stiffness

$$\ell_o = \frac{I_o \ell_i}{2I_i}\left(\frac{I_p - I_i}{I_o - I_p}\right) \tag{20}$$

with I_i, I_o and I_p moment of inertia of the inner portion cross section, of the outer portions cross section and of the original standard profile, respectively;

9. finally, for all the effected steps, the relevant device volume is calculated

$$V = 2\ell_o A_o + \ell_i A_i \tag{21}$$

with A_i and A_o area of the inner portion cross section and of the outer portions cross section, respectively, and the optimal design of the device is eventually chosen as the one which minimizes the total volume.

4. Results and discussions

In the present section, some applications will be presented in order to proof the good reliability and the simplicity of the proposed sub-optimal design procedure. Two cross-sections are considered, an IPE300 and an HEA300, and two different level of bending resistance reduction $\alpha = 0,4$ and $\alpha = 0,7$ are also considered.

The discrete value assumed for the internal level arm in the reference steps are:

$$h_d^{*(\text{IPE300})} = [26 \quad 26,5 \quad 27 \quad 27,5 \quad 28 \quad 28,5] \tag{22}$$

$$h_d^{*(\text{HEA300})} = [25 \quad 25,5 \quad 26 \quad 26,5 \quad 27 \quad 27,5] \tag{23}$$

For each of these values, basing on the reduction of resistance required, the relevant values for the inner portion flange thicknesses are obtained. Consequently, the check of the ductility class for the resulted cross section is executed, and in case of class equal or less than class 2 (see, [13]-[15]), the procedure moves forward to the computing of the remaining outer quantities. On the contrary, if the obtained cross section is a class 3 or 4, its base width is gradually decreased till the cross section respects at least class 2. Completing the further step of the sub-optimal procedure, the full results of the design problems are obtained (Table 1).

Table 1. Sub-optimal results for the selected profiles.

	IPE 300		HEA 300	
α	0.4	0.7	0.4	0.7
h^*	27.5	27.5	26.0	26.0
$t_{f,o}$	2.5	2.5	3.0	3.0
$t_{f,i}$	0.427	0.751	0.844	1.219
ℓ_o	30.613	8.482	30.377	8.971
ℓ_i	15	15	14.5	14.5
t_w	0.71	0.71	0.85	0.85
Reduction %	33%	-	38%	13%
b_n	10.05	-	18.6	26.1
V	4639.7	2210	8816.6	4424.5

In order to evaluating the reliability of the simplified proposed procedure each design was subjected to computational proofs by plotting the relevant plastic domains and by carrying out appropriate FEM analyses with the software Simulia Abaqus. For the sake of brevity, the results related to just two examples are reported in figure 3a,b and in figure 4a,b where the full development of the plastic deformation within the inner portion in correspondence of the assigned limit bending moment is shown.
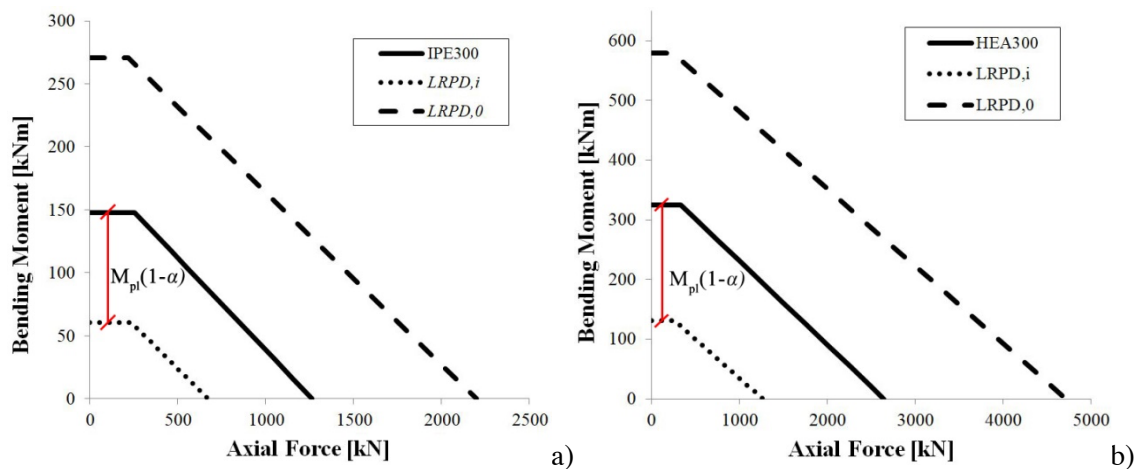
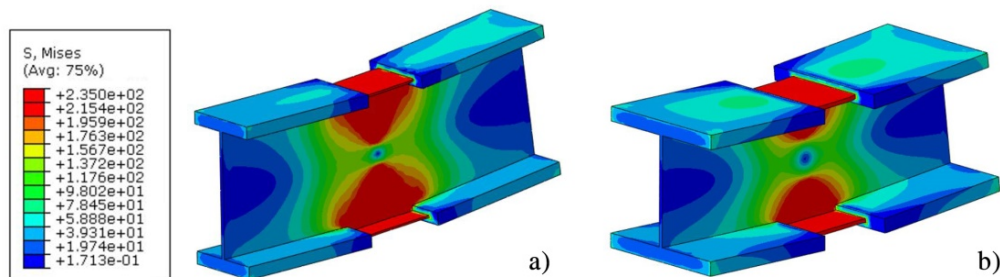**Figure 3.** Plastic N-M domain: a) IPE300; b) HEA300.

Figure 4. Von Mises stress distribution for the assigned limit bending strength:
a) IPE 300 profile; b) HEA 300 profile.

5. Conclusions

In the present paper an iterative procedure devoted to reaching the optimal design of some new moment resisting devices (*LRPD*) has been formulated. For the sake of simplicity and with the aim of proposing an approach widely usable in practical applied engineering, reference has been made to plane structure in pure bending.

The proposed procedure consists of nine simple steps, it does not need of special computational software, and it provides a solution very reliable. The exact solution, taking into account the axial force contribution, could be reached by formulating a continuous variable optimal design for the device, and it will be object of future studies. The effected applications have been carried out by making reference to two standard profiles: a IPE300 and a HEA300, utilizing steel type S235. For the different studied cases ($\alpha = 0.4$ and $\alpha = 0.7$) the relevant optimal designs have been determined by solving the described iterative computational procedure.

As stated before, the obtained designs respect all the desired requirement: they appertain to class 1 or class 2 I-cross section, the expected plastic deformation occur in correspondence of the imposed limit bending values and are located just in the inner portion of the devices, the elastic stiffness equals the analogous quantity of the reference standard beam element. All these good features have been verified by means of finite element analyses developed in ABAQUS environment.

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