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Welded section defence by LRPD devices

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Abstract

The present paper concerns a special application of some recently proposed structural devices, called LRPD, able to protect the welded sections of frame steel structures from undesired brittle collapse ensuring the good expected ductile behaviour. Standard I-shaped cross-sections are treated, and the proposed devices are suitably considered as moment resisting connections between beams and columns. At first the domain representing the brittle safe conditions is defined in the N, V, M space; then a sample plane frame subjected to seismic load conditions is studied and it is proved that, equipping the structure with the proposed devices suitably designed, the generalized stresses at the welded sections remain within the relevant brittle safe domain and the structure is able to dissipate a significant amount of plastic dissipation energy.

Keywords: welded cross-sections; protecting devices; frame structure behaviour.

1. Introduction

Nowadays steel structures (SS), constituting the framework of industrial and/or civil constructions, are the most adopted ones due to their durability and extreme versatility of the geometric scheme they can arrange. Often SS are constituted by several plane frames combined together to fulfill the construction functionality. Among the fundamental characteristics of steel structures probably the most important one is their ability to exhibit a safe behaviour for high intensity loads due to their intrinsic ductility features even if local damages can occur, as in the

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case of the elastic or plastic shakedown behaviour (see, e.g., Benfratello et al. (2015), Benfratello et al. (2017), Magisano and Garcea (2020), Benfratello et al. (2020a), Zhang et al. (2021)).

In the framework of steel frames, generally the most dangerous actions are located at nodes where the connection between beams and columns is very often realized by welding. As it is well known, welding can produce a modification of the material crystal lattice and, consequently, the transition from a ductile behaviour to a brittle one. Therefore, to avoid such undesired behaviour it is reasonable to introduce in the design stage suitable approaches to protect welding sections.

This can be made simply by reducing the structural stresses acting on the welded sections. To this goal, in the present paper, the adoption of a new moment resisting connection device able to limit the actions on the welded sections with no change in the overall elastic structural behaviour and to develop plastic deformations in suitably selected portions of the structure is proposed. This device is known as Limited Resistance Plastic Device (LRPD) and it is deeply examined in many previous papers of the same authors (see, Benfratello and Palizzolo (2017), Benfratello et al. (2017), Benfratello et al. (2019), Palizzolo et al. (2019), Benfratello et al. (2020b), Benfratello et al. (2020c), Benfratello et al. (2021), Benfratello et al. (2022a)), where the different optimal designs proposed, and the numerical test performed are reported. Recently an experimental campaign on the behavior of this device has been started and the first results are reported in Benfratello et al (2022c). The proposed device can be framed in RBS moment connection which is a very important topic in literature (see, e.g., Plumier (1997), Miller (1998), Shen et al. (2000), Saleh et al. (2016), Horton et al. (2021), Benfratello et al. (2022d=) and widely adopted in international codes (see, e.g., AISC 2016, EN 1993-1-8 2006).

In the present paper the LRPDs will be designed on the grounds of a suitable brittle rupture surface defined in the space of normal force, shear force and bending moment and the plane frame will be designed for seismic actions. It will be shown that, due to LRPDs, welded sections are suitably protected ensuring the onset of a great amount of energy dissipation.

Nomenclature

σ_b	brittle limit normal stress
τ_b	brittle limit shear stress
$\sigma_{I,II}$	principal stresses
σ_x	normal stress along x axis
τ_{xy}, τ_{xz}	tangential stresses
N^E	elastic limit axial force
A	area of the cross-section
V^E	elastic limit shear force
I_y	moment of inertia with respect to y axis
$S'_y(\cdot)$	static moment with respect to y axis
a	web thickness
e	flanges thickness
b	cross-section width
h	cross-section height
M^E	elastic limit bending moment
W_y^E	cross-section elastic resistance modulus with respect to the y axis
$\overline{N}, \overline{V}, \overline{M}$	fixed values of axial force, shear force and bending moment
E	material Young modulus
p	distributed load
G_1, G_2	dead and permanent loads
Q_k	variable load
q	behaviour factor

2. Definition of the brittle safe domain

Following the Tresca criterion, the significant limit condition in plane stress holds

$$|\sigma_I - \sigma_{II}| = \sqrt{\sigma_x^2 + 4\tau_{xy}^2 + 4\tau_{xz}^2} = \sigma_b \tag{1}$$

Making reference to the typical I-shaped cross-section sketched in Fig. 1, at extrados and intrados, the condition reads

$$|\sigma_I - \sigma_{II}| = \sqrt{\sigma_x^2 + 4\tau_{xy}^2} = \sigma_b \quad \Longrightarrow \quad \sigma_x^2 + 4\tau_{xy}^2 = \sigma_b^2 \tag{2}$$

and within the web the condition reads

$$|\sigma_I - \sigma_{II}| = \sqrt{\sigma_x^2 + 4\tau_{xz}^2} = \sigma_b \quad \Longrightarrow \quad \sigma_x^2 + 4\tau_{xz}^2 = \sigma_b^2 \tag{3}$$

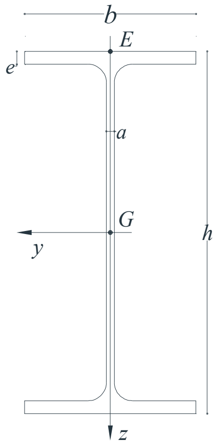


Fig. 1. Geometry of the typical I-shaped cross section.

Moreover, it results:

$$N^E = A\sigma_b; \quad V^E = \frac{\sigma_b I_y a}{2S_y'(G)}; \quad M^E = W_y^E \sigma_b. \tag{4}$$

In the previous equations $\tau_b = \sigma_b/2$ has been assumed.

<u>Domain boundary on N, M plane</u>

The domain boundary on the first quarter of the N, M plane is defined by the function

$$\frac{N}{A} + \frac{M}{W_y^E} = \sigma_b, \quad \forall\, N \in (0; N^E), \ \forall\, M \in (0; M^E). \tag{5}$$

On the other quarters of the plane the boundary can be defined imposing symmetry with respect to the N and M axes (Fig. 2a).

<u>Domain boundary on N, V plane</u>

The domain boundary on the first quarter of the N, V plane is defined by the function

$$\left(\frac{N}{A}\right)^2 + 4\left[\frac{VS_y'(G)}{I_y a}\right]^2 = \sigma_b^2, \quad \forall\, N \in (0; N^E),\ \forall\, V \in (0; V^E). \tag{6}$$

On the other quarters of the plane the boundary can be defined imposing symmetry with respect to the N and V axes (Fig. 2b).

Domain boundary on V, M plane

The domain boundary on the first quarter of the V, M plane is defined by combining the function

$$\left(\frac{M}{W_y^E}\right)^2 + 4\left[\frac{VS_y'(E)}{I_y e}\right]^2 = \sigma_b^2, \ \forall\, V \in (0; V^E),\ \forall\, M \in (0; M^E), \tag{7}$$

and the discrete set of couples of values of shear force and bending moment obtained by the solution to the following minimum problem:

$\min_{(z)} M$ subjected to

$$\left(\frac{M}{I_y} z\right)^2 + 4\left[\frac{\overline{V}S_y'(z)}{I_y a}\right]^2 \geq \sigma_b^2, \ \forall\, \overline{V} \in (0; V^E),\ \forall\, z \in \left(0; \frac{h}{2} - e\right). \tag{8}$$

On the other quarters of the plane the boundary can be defined imposing symmetry with respect to the V and M axes (Fig. 2c).

Domain boundary surface on the first octant of N, V, M space

The domain boundary surface on the first octant of N, V, M space is defined by combining the function

$$\left(\frac{N}{A} + \frac{M}{W_y^E}\right)^2 + 4\left[\frac{\overline{V}S_y'(E)}{I_y e}\right]^2 = \sigma_b^2, \ \forall\, \overline{V} \in (0; V^E), \tag{9}$$

which provides a discrete set of functions N, M in correspondence to an analogous discrete set of values of $\overline{V}$, and the discrete set of values of axial force, shear force and bending moment obtained by the solution to the following minimum problem:

$\min_{(z)} V$ subjected to

$$\left(\frac{\overline{N}}{A} + \frac{\overline{M}}{I_y} z\right)^2 + 4\left[\frac{VS_y'(z)}{I_y a}\right]^2 \geq \sigma_b^2, \ \forall\, \overline{N} \in (0; N^E),\ \forall\, \overline{M} \in (0; M^E),\ \forall\, z \in \left(0; \frac{h}{2} - e\right), \tag{10}$$

for a prefixed discrete set of couples of values of $\overline{N}$ and $\overline{M}$. On the fifth octant the boundary surface can be defined imposing symmetry with respect to the N, M plane.

Domain boundary surface on the fourth octant of N, V, M space

The domain boundary surface on the fourth octant of N, V, M space is defined by combining the function

$$\left(\frac{N}{A} - \frac{M}{W_y^E}\right)^2 + 4\left[\frac{\overline{V}S_y'(E)}{I_y e}\right]^2 = \sigma_b^2, \ \forall\, \overline{V} \in (0; V^E), \tag{11}$$

which provides a discrete set of functions N, M in correspondence to an analogous discrete set of values of $\overline{V}$, and the discrete set of values of axial force, shear force and bending moment obtained by the solution to the following minimum problem:

$\min_{(z)} V$ subjected to

$$\left(\frac{\overline{N}}{A}-\frac{\overline{M}}{I_y}z\right)^2+4\left[\frac{VS_y'(z)}{I_y a}\right]^2\geq\sigma_b^2,\ \ \forall\,\overline{N}\in(0;N^E),\ \forall\,\overline{M}\in(-M^E;0),\ \forall\,z\in\left(e-\frac{h}{2};0\right),\tag{12}$$

for a prefixed discrete set of couples of values of $\overline{N}$ and $\overline{M}$. On the eighth octant the boundary surface can be defined imposing symmetry with respect to the N, M plane.

Domain boundary surface on the second octant of N, V, M space

The domain boundary surface on the second octant of N, V, M space is defined by combining the function

$$\left(\frac{N}{A}-\frac{M}{W_y}\right)^2+4\left[\frac{\overline{V}S_y'(E)}{I_y e}\right]^2=\sigma_b^2,\ \ \forall\,\overline{V}\in(0;V^E),\tag{13}$$

which provides a discrete set of functions N, M for an analogous discrete set of values of $\overline{V}$, and the discrete set of values of axial force, shear force and bending moment obtained by the solution to the following minimum problem:

$$\min_{(z)} V \ \ \text{subjected to}$$

$$\left(\frac{\overline{N}}{A}-\frac{\overline{M}}{I_y}z\right)^2+4\left[\frac{VS_y'(z)}{I_y a}\right]^2\geq\sigma_b^2,\ \ \forall\,\overline{N}\in(-N^E;0),\ \forall\,\overline{M}\in(0;M^E),\ \forall\,z\in\left(e-\frac{h}{2};0\right),\tag{14}$$

for a prefixed discrete set of couples of values of $\overline{N}$ and $\overline{M}$. On the sixth octant the boundary surface can be defined imposing symmetry with respect to the N, M plane.

Domain boundary surface on the third octant of N, V, M space

The domain boundary surface on the third octant of the N, V, M space is defined by combining the function

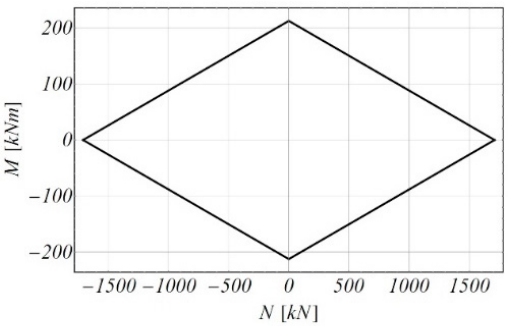
$$\left(\frac{N}{A}+\frac{M}{W_y}\right)^2+4\left[\frac{\overline{V}S_y'(E)}{I_y e}\right]^2=\sigma_b^2,\ \ \forall\,\overline{V}\in(0;V^E),\tag{15}$$

which provides a discrete set of functions N, M in correspondence to an analogous discrete set of $\overline{V}$ values, and the discrete set of axial force, shear force and bending moment values solution to the following minimum problem:

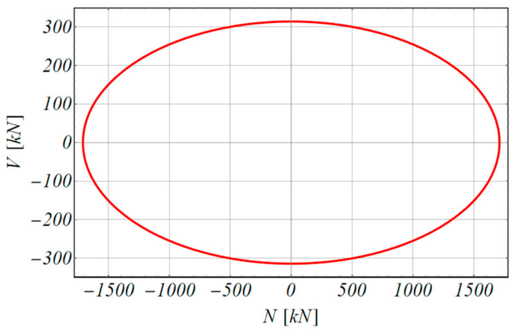
$$\min_{(z)} V \ \ \text{subjected to}$$

$$\left(\frac{\overline{N}}{A}+\frac{\overline{M}}{I_y}z\right)^2+4\left[\frac{VS_y'(z)}{I_y a}\right]^2\geq\sigma_b^2,\ \ \forall\,\overline{N}\in(-N^E;0),\ \forall\,\overline{M}\in(-M^E;0),\ \forall\,z\in\left(0;\frac{h}{2}-e\right),\tag{16}$$

for a prefixed discrete set of couples of values of $\overline{N}$ and $\overline{M}$. On the seventh octant the boundary surface can be defined imposing symmetry with respect to the N, M plane. The overall domain in the N, V, M space is reported in Fig. 2d in the case of IPE360 profile.



a)



b)

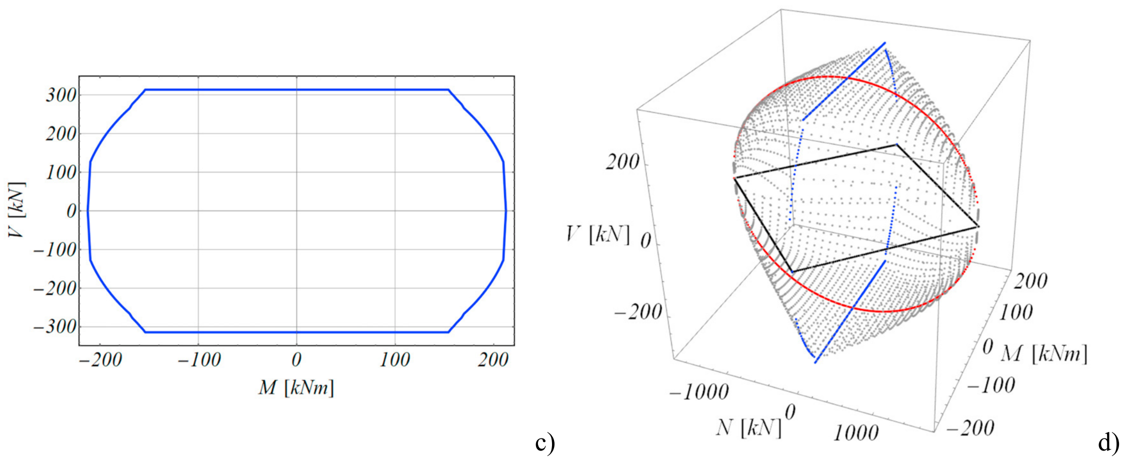


Fig. 2. Elastic domains for IPE360 profile: a) N, M; b) N, V; c) M, V; d) N, V, M.

3. Application

Let us consider the plane frame sketched in Fig. 3.

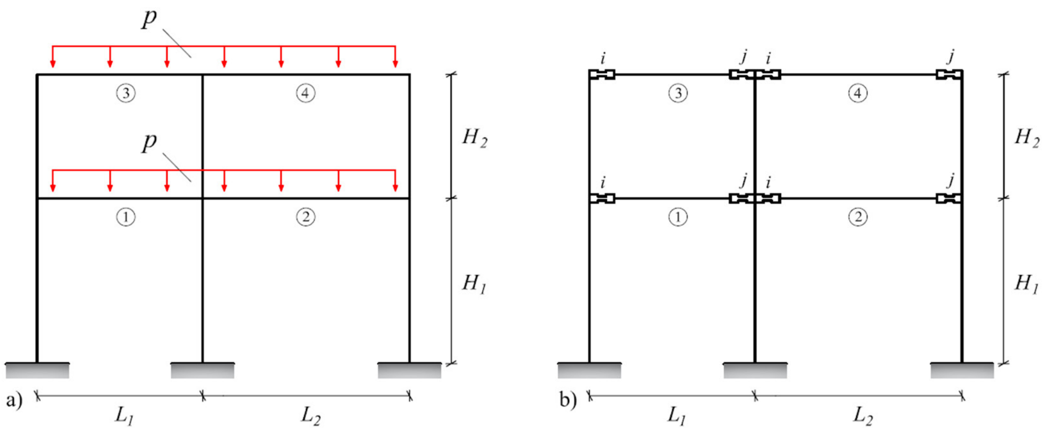


Fig. 3 – Steel plane frame: a) geometry and load condition; b) position of the LRPD.

The material constituting the frame is a steel S275 grade ($E = 210.000$ MPa). The geometrical data are: $L_1 = 4$ m; $L_2 = 5$ m; $H_1 = 4$ m; $H_2 = 3$ m. The distributed load $p = 45$ kN/m is the sum of $G_1 = 18$ kN/m, $G_2 = 12$ kN/m and $Q_k = 15$ kN/m. Beams 1 and 3 are constituted by HEA220 profiles, beams 2 and 4 are constituted by HEA260 profiles. The columns are constituted by HEB340 profiles.

This frame has been already studied in Benfratello et al. (2022b), where the selected frame has been designed with behaviour factor $q = 4$, referring to the considered Italian code. The same analysis has been analyzed with behaviour factor $q = 1$ obtaining, as expected, that the beam element extremes suffer load conditions above the related elastic domain. These values have been utilized for designing the LRPD devices. Referring for the sake of brevity to the previously cited papers for the device geometry description and imposing, as usual, for the internal portion length $\ell_i = 0.5h$, the optimal design problem results are listed in Benfratello et al. (2022b). To confirm the affordability of LRPD as device to limit the actions on the welded sections in the cited reference both frames were studied by performing a non-linear dynamic analysis subjected to an assigned seismic time history compatible with the response spectrum. The results confirms that the frame equipped with LRPD exhibits a generalized stress response brittle safe.

Moreover, in the present paper both the frames, equipped or not with LRPD, are studied to analyse their ability to develop plastic deformations and, consequently, to dissipate energy. To reach this goal the first step has been to verify the ability of LRPD to dissipate energy and, therefore, a cyclic analysis of a LRPD designed for an HEA 260 profile with a limit bending moment equal to 0.55 of that of HEA260 has been performed. The results, in terms of dimensionless bending moment vs dimensionless curvature, are reported in Fig. 4 (M_p and K_p are the limit bending moment and the corresponding curvature of HEA 260 profile). As second step both frames have been subjected to a nonlinear static cyclic load history simulating the seismic actions. The results are reported in Fig. 5 in terms of load-deflection and they confirm the ability of LRPD of dissipating a great amount of energy.

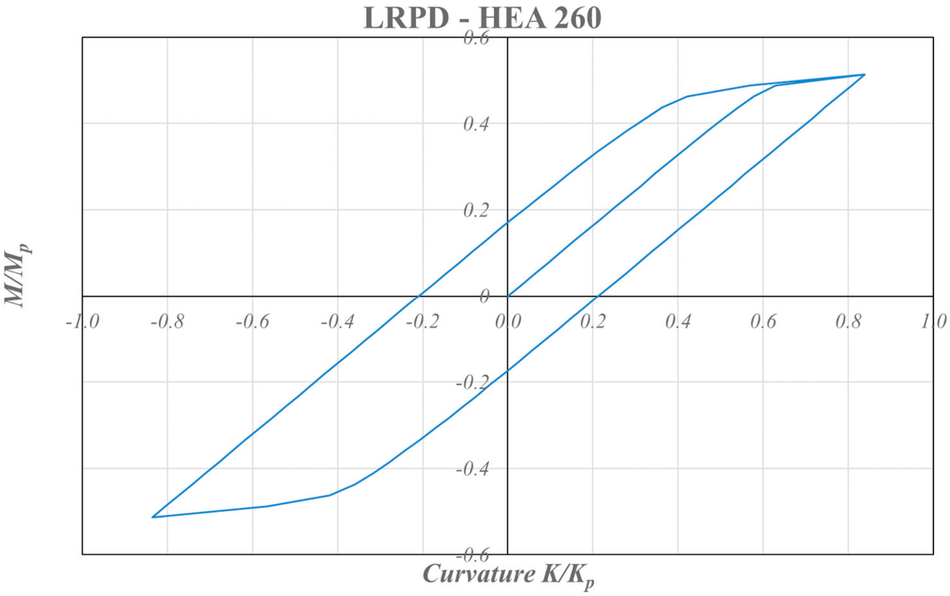


Fig. 4 – Dimensionless bending moment vs dimensionless curvature for LRPD designed for HEA260 profile.

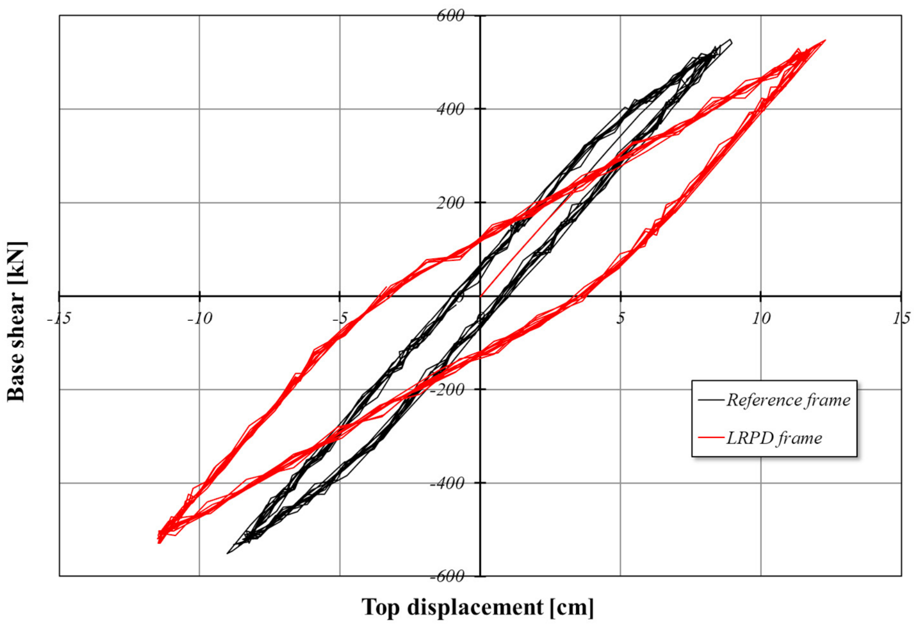


Fig. 5 – Load-deflection curves for the analyzed frames.

4. Conclusions

In the present paper, a special strategy devoted of limit the generalized stresses acting on the welded cross-sections of a steel frame structure by making use of some innovative devices for beam-column connections, able to preserve the node integrity without modifying the elastic behaviour and fully exploiting the material ductile features, is proposed.

The computational procedure consists of evaluating the limit elastic bending moment on the relevant cross-sections complying the reference N, V, M domain and designing the LRPD devices for the assigned limit stress values able to prevent brittle behaviour as a percentage of elastic limit stress suitably selected depending on the welding methodology. The performed numerical applications, related to a simple plane frame, confirm the effectiveness of the proposed strategy.

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