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The influence of the geometric characteristics on the behavior of braces with restrained buckling - case study of perforated steel core.

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Abstract. Buckling restrained braces are elements that equip the building with additional capacity for resistance and stability when subjected to earthquakes. As an answer to the problem of the possible loss of stability of the buckling-preventing component, the "perforated-core buckling restrained braces" (PCBRB) is a concept that involves the introduction of gaps, in the core of the bracing, to control the plasticizing mechanism of the dissipative element. The research addresses the behavior of PCBRB groups where all the elements belonging to the same group have the same area and length of the section considered active dissipative. A numerical analysis environment was developed that simulates the support conditions and material behavior. Based on the results of the numerical analyses, the influence of the geometry (b/t ratio) of the section of the dissipative zone on the behavior and the mechanism of stress strain distribution in the bracing core. It can be noticed the development of over-resistance to the compressive stress and non-uniform distribution of stresses on the surface of the elements whose b/t ratio exceeds the value of 5.5; for the elements whose b/t ratio has a value lower than 1.75 local instability problems in the dissipative zone occurred.

1. Introduction

Buckling restrained braces (BRB) are a type of dissipative elements, with a hysteretic behavior whose theoretical concept appeared for the first time at the end of the 80s. In 1988, the team of researchers cited in bibliographic sources [1-3] developed and tested the first fully functional bracing model with prevented buckling. Based on the promising results obtained experimentally, this type of control elements of the displacements of structures has been adopted in several countries since the end of the 90s.

The functionality of these elements is based on the deformation of the metal core as the dissipative component, and on the ability of the buckling prevention component to block the movements in the transversal directions of the core, when subjected to compression. Thus, the control component of the core movements must, at the same time, ensure the stability under the compressive stress of the dissipative component (the BRB core), while allowing at the same time the free, unobstructed movement of the core under the action of the tensile stress.

This behavior requires the introduction of a theoretical layer, first in the design and numerical analysis stage and later applied in the manufacturing stage, as a physical layer, with well-defined elastic characteristics. It allows the movement of the steel core inside the control component along the direction of the axial force. The initial concept proposed a ductile steel core as a dissipative component, and a sleeve composed of a steel pipe filled with concrete as a displacement control element - figure 1.

Relatively recent studies on these movement control elements have highlighted a series of inconveniences, as well as some territories to be further investigated in order to improve the concept.

In specialized literature, certain studies published in 2010 [4], there is highlighted the phenomenon of the local stability loss of the buckling prevention element. Under the effect of the seismic action, the displacements and deformations of the BRB core produce lateral thrusts on the elements that ensure the stability under the axial forces of the core, a fact that, under certain conditions, can lead to the premature failure of the buckling prevention mechanism.

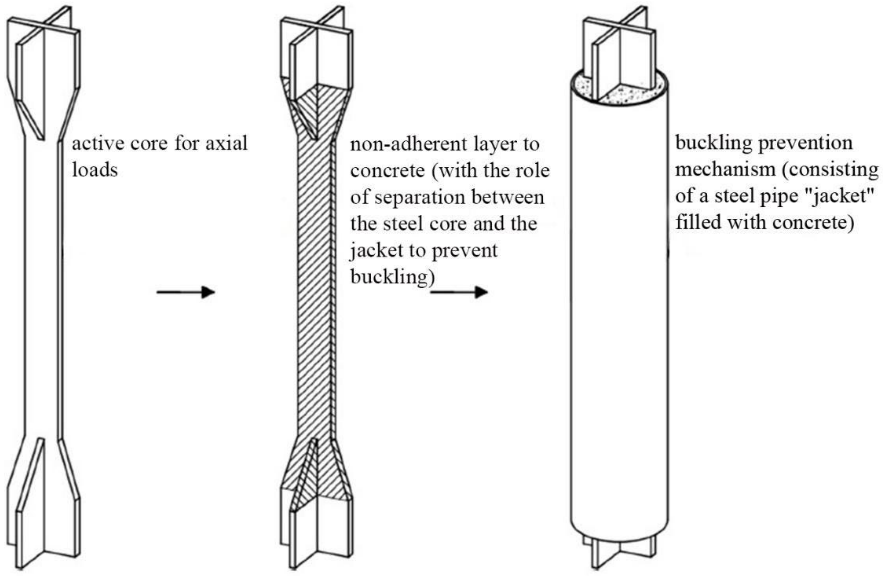

Figure 1. Conceptual system of the BRB [6].

The manufacturing process of BRB revealed the dependency of the implementation of the dissipative elements on the maturation time of concretes and high-strength mortars based on cement binders. The maturation time of concrete and mortar based on cement binders is considered at least 28 days.

The limited predictability of seismic actions means that the implementation/activation of the BRB is not recommended before reaching the characteristic resistances of the prevention mechanism.

After implementation, the inspection of the dissipative component (of the BRB core) becomes impossible due to its constructive nature. Due to the same closed box feature of the blocking mechanism, the replacement of the damaged elements for various reasons (accidental loads, seismic events, etc.) becomes impossible.

The above led to the need to investigate new methods of controlling the deformation mode of the BRB core as well as to furthering the implementation of new constructive concepts of buckling control mechanisms. The first requirement indicated above is addressed by putting into practice the concept of perforated BRB core (PCBRB).

Practically, in order to limit the axial stress within the elements of the buckling prevention component, a series of gaps are imposed along the core. In this way, in this way, as presented and concluded in previous research works [5-8], the axial deformations of the dissipative core are directed inside this gap, the stress induced on the hindering elements being diminished.

Other proposal [7] suggests that the buckling control elements should be made of thick sheet metal plates assembled with screws (figure 2), that would significantly reduce the manufacturing and implementation time of the BRB and would allow a periodic inspection of all the component elements.

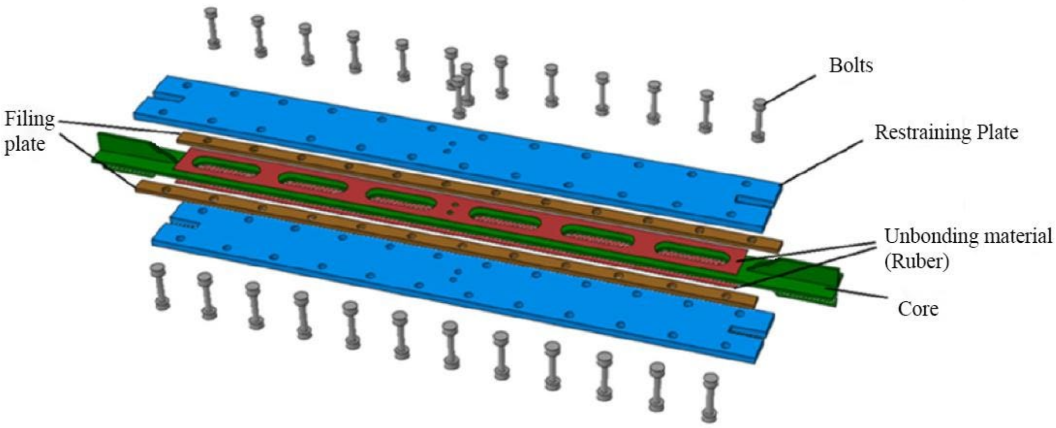

Figure 2. Conceptual system of "dry" BRB [7].

2. The research objective

The computation relationships of the classical stability factors (Euhler's theory) have limited applicability in this specific situation. The Bernoulli's hypothesis this theory is based upon (that refers to the flat and perpendicular sections to the initial axis of the element remaining the same after deformation occurred), lead to the approximate behavior of the materials. Also, this calculation hypothesis fails to capture the variable nature of the longitudinal modulus of elasticity (E) under cyclic actions, in the situation where the value of deformation or stress exceeds the limit of the material's elastic behavior. However, one cannot ignore the importance of the geometric characteristics that are the basis of the calculation principle of the stability factor, in particular the moment of inertia and the buckling length of the analyzed element.

As highlighted as presented and concluded in previous research works [5-8], the slenderness ratio can provide a preliminary prediction on the stability of PCBRB; this influence needs further investigation. The study developed in this paper focuses on the influence of the length of the elastic zone that delimits the gaps and at the same time ensures the stability of the plastic elements, upon the formation of the isostatic lines of 1st and 2nd ranks.

Starting from Navier's relationship that results in the computation of the normal stresses σ, and taking into account the fact that the area of the section (which in the studied case undergoes variations) directly influences the value of the stresses, the excessive presence of an area with a larger section, implicitly leads to a stress reduction on the respective area, thus reducing the deformable potential of the respective area. Figure 3 shows the conceptual model of PCBRB, the core areas and the interspaced gaps, highlighting the following geometrical characteristics:

- Lt – the total length of the PCBRB;
- Lea - the elastic length of the anchorage - the end zone of the PCBRB, that must be sized to display throughout the load/deformation cycle an elastic behavior;
- Lp - the plastic deformation length - the zone that is taken into account as a dissipative component;
- Let - the elastic length of the zone that ensures the stability of the median strips that sum up the dissipative component of the core;

- Lem – the length of the elastic-median zone - the zone that will also ensure the physical connection between the dissipative component and the buckling control component of the BRB.

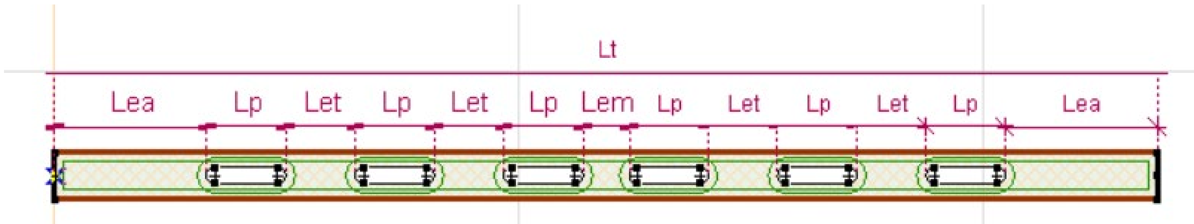

Figure 3. The PCBRB model and the delimitation of areas.

A final objective focuses on the distribution and values of the reactions that will be actually delivered by the PCBRB core to the buckling prevention elements. The Romanian Norm P100/2013 acknowledges the buckling-restrained bracing as „… dissipative elements that are designed to develop significant plastic deformations when subjected to the design value of the seismic action. The braces are made from a steel core inserted in a system that prevents the buckling of the core" [9].

The axial deformations of the BRB core will produce lateral thrusts towards the buckling prevention elements. In 2017, Stratan et al. [10] proposes a safety factor with a value of 3 between the critical buckling force of the buckling prevention elements and the maximum plastic capable force of the core.

Summarizing the above-mentioned facts, this study focuses on the followings:

- the influence of the slenderness ratio, along the two orthogonal directions of the PCBRB section, on stability against buckling;
- the influence of the buckling length of the plastic zone on the behavior of the PCBRB (figure 4).

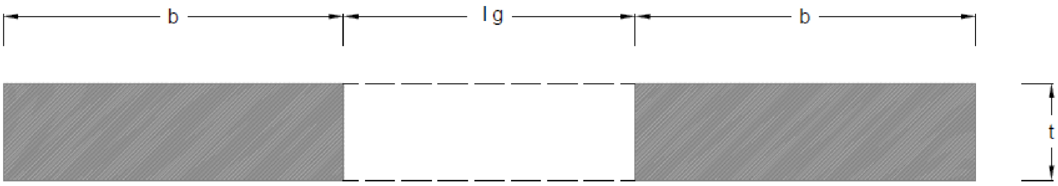

Figure 4. The geometrical characteristics of the plastic section: *b* – the section width, *lg* – the gap width, *t* – the core thickness.

3. Input parameters for the numerical simulations

S235JRZ15 steel type was chosen as the PCBRB material for the next series of experimental numerical tests; the corresponding mechanical characteristics are presented in table 1.

Table 1. Mechanical characteristics

Material	f_y [N/mm^2]	f_u [N/mm^2]	f_u/f_y [-]	ε [%]
S235JRZ15	235	360	1.532	15

One of the material feature is the high value of the self-consolidation factor as the ratio between the value of the ultimate stress and the value of the yielding stress. In order to highlight the influence of the geometric characteristics on the stability of the behavior of PCBRB subjected to cyclic loads, a series of groups of PCBRB elements with the following characteristics were defined:

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- all models in the same group have the same plastic section area;
- all analyzed models have the same total length;
- all models in the same group have the same Lp;
- the sectional characteristic *t* is varied (as presented in figure 4) for the elements from the same group, taking into account the delivery availability of suppliers on the European market.

In table 2 and in figure 5, the variation of the characteristics and geometries of the elements in the test group with area equal to 700 mm^2 is presented.

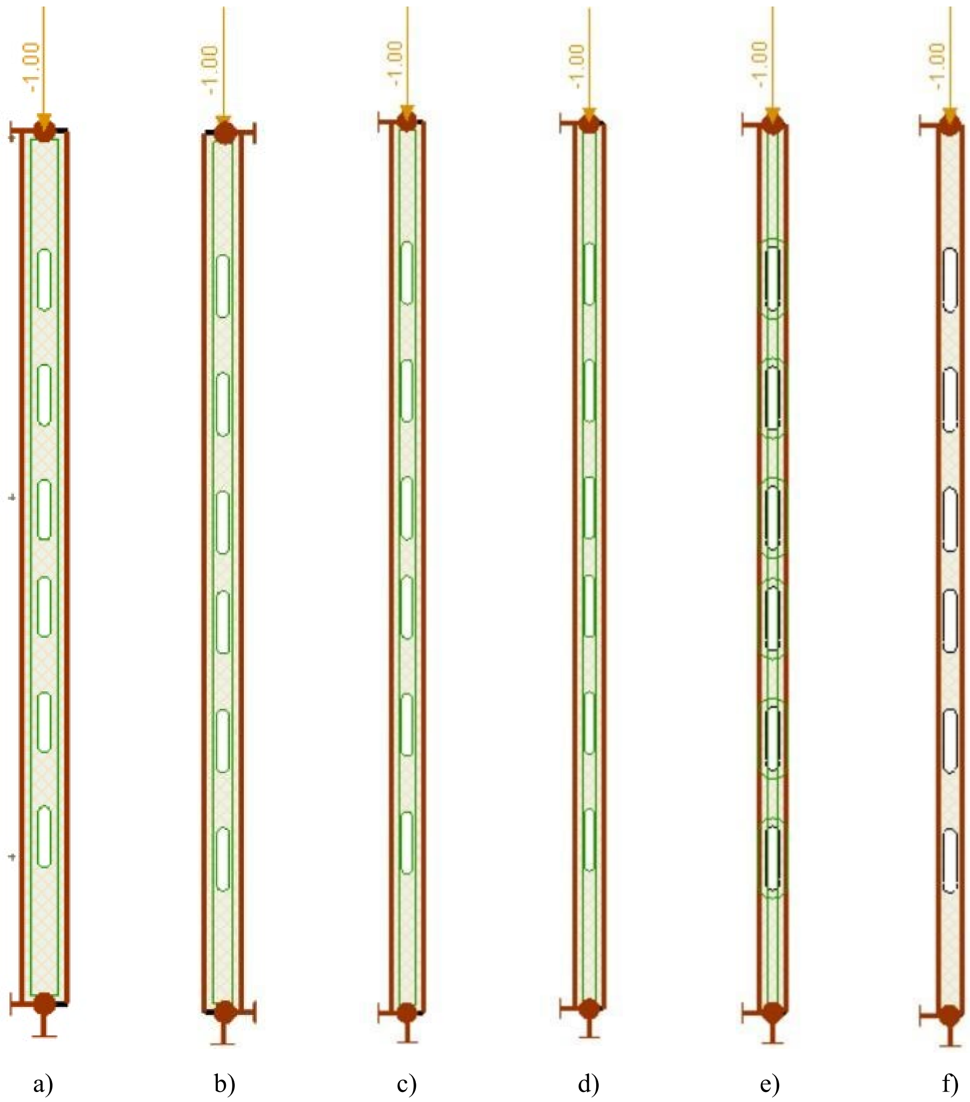
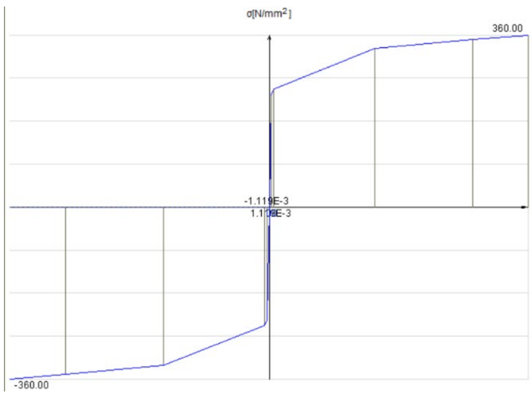


Figure 5. Geometry of the PCBRB group with area 700 mm^2: a) PCBRB 8*43, b) PCBRB 10*35, c) PCBRB 12*29, d) PCBRB 15*23, e) PCBRB 20*17, f) PCBRB 20*14.

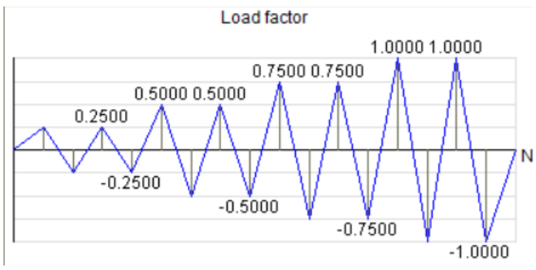
Table 2. Sectional characteristics for the groups with the area of 700 mm^2

Geometrical characteristic	PCBRB 8*43	PCBRB 10*35	PCBRB 12*29	PCBRB 15*23	PCBRB 20*17	PCBRB 25*15
t [mm]	8	10	12	15	20	25
b [mm]	43.75	35	29.167	23.33	17.5	15
I_y [mm^4]	55826.82	35729.17	24811.92	15879.63	8932.29	5716.67
I_x [mm^4]	1866.67	2916.67	4200	6562.50	11666.67	18229.17
i_y[mm^2]	8.93	7.14	5.95	4.76	3.57	2.86
i_x [mm^2]	1.63	2.04	2.45	3.06	4.08	5.10
λ_y	9.52	11.89	14.27	17.85	23.76	29.74
λ_x	52.05	41.64	34.70	27.76	20.82	16.65
b/t	5.47	3.5	2.43	1.55	0.87	0.56
λ_x/λ_y	5.47	3.5	2.43	1.55	0.87	0.56
L_p [mm]	170	170	170	170	170	170

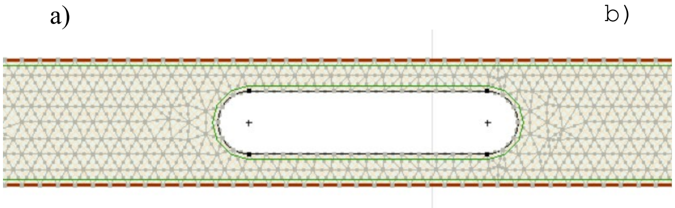
The geometries of the elements that are the subject of this study were modeled using the FEM AxisVM6 program. For all analyzed PCBRB models, the same support conditions, material behavior and cyclic loading were considered. The material behavior was modeled using von Mises' isotropic plasticization model, based on a multipoint characteristic curve of the material figure 6a. In defining the characteristic curve in the program, it was aimed to capture as accurately as possible all the inflection points considered relevant. A cyclic loading program whose characteristics correspond to the model described by European regulations [11] (figure 6b) was applied. All the models with the same type of finite element were discretized, with a maximum size of 10 mm to capture the stress state developed in the entire material mass (figure 6c).



a)



b)



c)

Figure 6. Characteristics of the PCBRB model: a) multipoint characteristic curve, b) cyclic load curve, c) discretization in finite elements.

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4. Numerical analysis and interpretation of the results

As mentioned in the previous chapters, the aim is to monitor the influence of the sectional characteristics on the stability and ductility of the analyzed PCBRB elements. As presented in table 2, the ratio between the two sides of the wing sections that form the active plastic length of the core is equal to the inverse ratio of the slenderness ratios, which derives from the calculation relationships of the sectional characteristics.

$$\lambda_y = \frac{l_f}{i_y} \tag{1}$$

where: λ_y – slenderness ratio according to the local axis y, l_f – the buckling length of the element, considered as half of Lp, i_y – radius of gyration of the section along the local axis y.

$$i_y = \sqrt{\frac{I_y}{A}} \tag{2}$$

where: Iy – the geometric moment of inertia along the local axis y, A – the cross-sectional area of a strip.

$$I_y = \frac{t*b^3}{12} \tag{3}$$

where: t- section thickness, b – section width

$$\frac{t}{b} = \frac{\lambda x}{\lambda y} \tag{4}$$

As the ratio between the two dimensions of the cross section equals the ratio between the slenderness along the two local axes of the section, the behavior dependency of the PCBRB to the slenderness ratio the b/t ratio will be further used. All the analyzed models presented the same deformation mode: the displacement of the lateral wings towards the hollow part under compressive stress (figure 7). Analyzing the stress distribution within all analyzed elements, the following conclusions can be formulated:

- the length of the gap does not influence the final failure criterion of the PCBRB element, but it directly influences the distribution and values of the normal stress within the element;
- the ratio of the two geometric characteristics b and t directly influences the normal stress distribution mode on the surface of the element.

The elements with a b/t higher than 4.5 show an unstable behavior during cyclic loads, the strains developed in the solid part of the element being up to 19% higher for stresses of tension than in compression (figure 7).

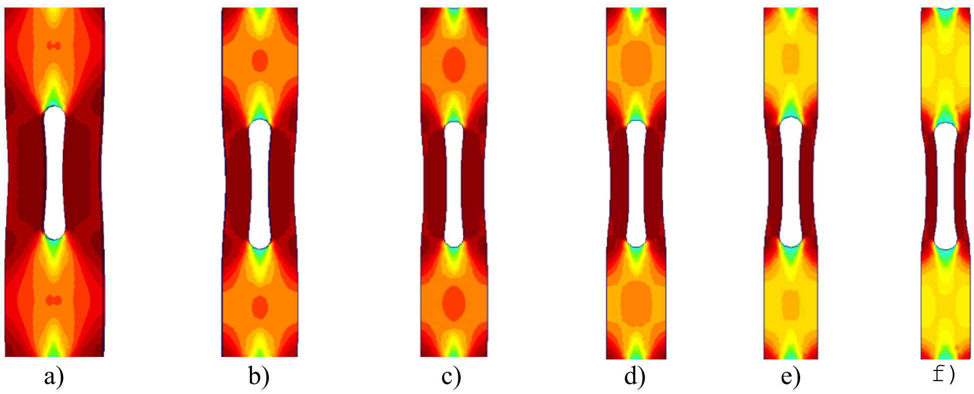

Figure 7. Plasticization and stress distribution in the analyzed elements: a) PCBRB 8*43, b) PCBRB 10*35, c) PCBRB 12*29, d) PCBRB 15*23, e) PCBRB 20*17, f) PCBRB 25*14.

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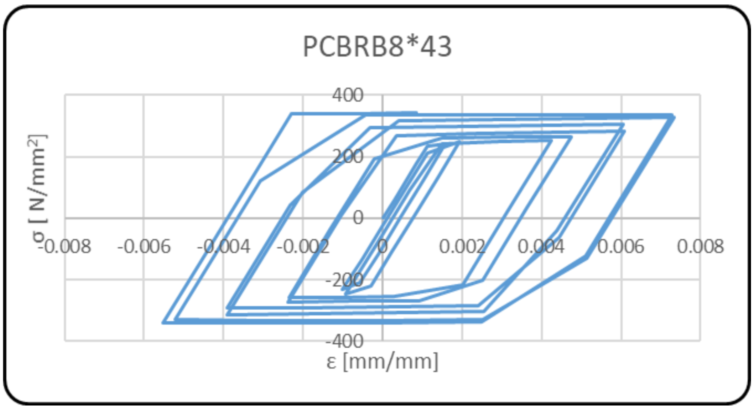
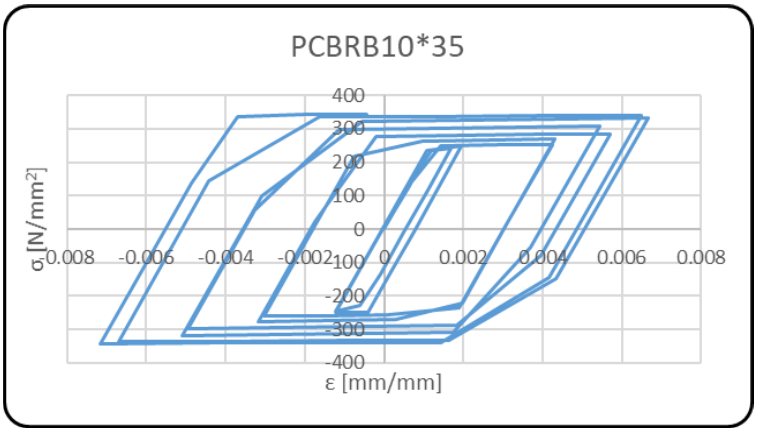


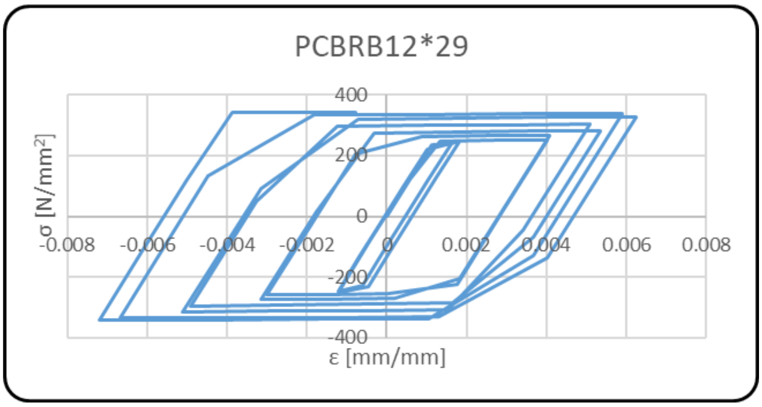
PCBRB8*43
b/t 5.46
σ 340.31
Cmax
ε Cmax 0.0055
3
σ 337.13
Tmax
ε Tmax 0.0074

Figure 8. Stress-strain curve for PCBRB 8*43



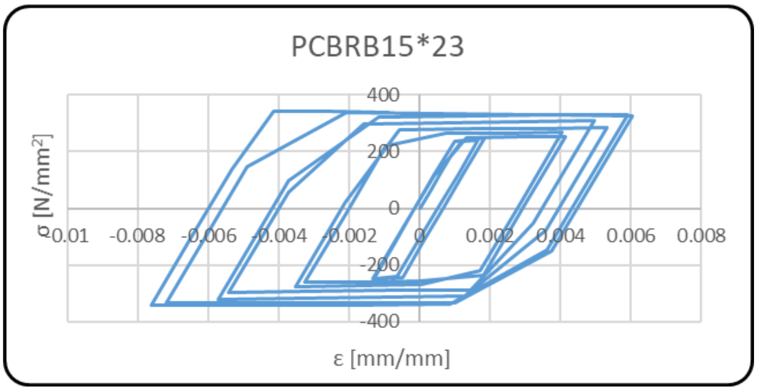
PCBRB 10*35
b/t 3.5
σ 342.48
Cmax
ε Cmax 0.0071
5
σ 332.15
Tmax
ε Tmax 0.0067

Figure 9. Stress-strain curve for PCBRB 10*35



PCBRB 12*29
b/t 2.43
σ 341.1
Cmax 7
ε Cmax 0.007
2
σ Tmax 328.7
ε Tmax 0.006
3

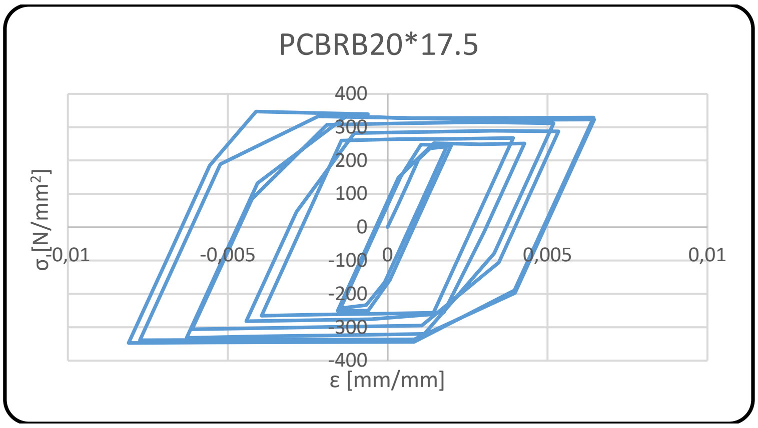
Figure 10. Stress-strain curve for PCBRB 12*29



PCBRB 15*23

b/t	1.55
σ Cmax	342.9
ε Cmax	0.0076
σ Tmax	327.18
ε Tmax	0.0062

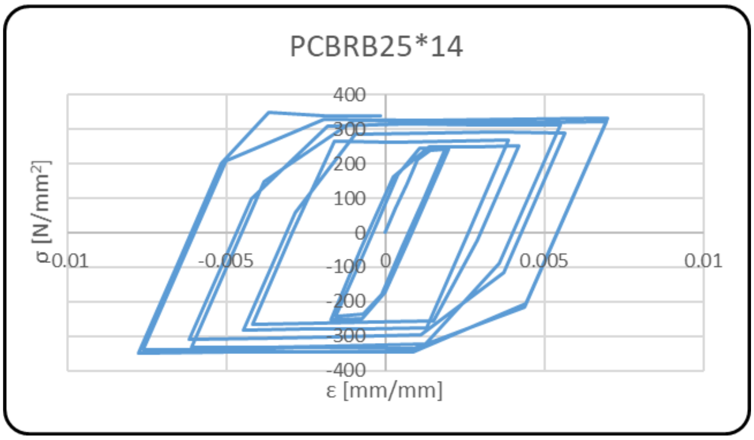
Figure 11. Stress-strain curve for PCBRB 15*23



PCBRB 20*17

b/t	0.875
σ Cmax	347.04
ε Cmax	0.0081
σ Tmax	323.12
ε Tmax	0.0065

Figure 12. Stress-strain curve for PCBRB 20*17.5



PCBRB 25*14

b/t	0.56
σ Cmax	348.63
ε Cmax	0.0078
σ Tmax	331.7
ε Tmax	0.0069

Figure 13. Stress-strain curve for PCBRB 25*14

However, it should be mentioned that in all groups, elements whose ratio b/t is less than 1.75, the software reported convergence problems between loading steps 80 and 85. This is due to the excessive deformation of the lateral bands that forms the plastic zone of the PCBRB core, under the action of compression stress. Consequently, further investigation will consider values of this ratio greater than 1.75. A similar effect is observed in the elements that present values of the b/t ratio greater than 4.5. These elements present two particularities: the initiation of the phenomenon of over-resistance to compression, and the non-uniform distribution of the normal stress on the entire plastic zone of the PCBRB. At the same time, for all the analyzed elements that are the subject of this discussion, a non-uniform stress distribution can be observed within the plastic zone. As it can be seen in figure 14 and in figure 15 for all these elements, the maximum values of the normal stress developed inside the solid of the plastic zone are directed towards the inner sides of the plastic zones. It can also be distinguished in the same figure the influence of Lp (of the length of the gap that defines the area of plastic deformation of the PCBRB) on the solid stress distribution. Thus, the length of the gap itself, which defines the area of plastic deformation of the PCBRB, cannot influence the behavior of the PCBRB, if the geometric characteristics of the section (b and t) are not taken into account. This phenomenon reflects the influence that the geometry of the cross-section has on the stability of the ductile behavior of PCBRB subjected to cyclic stretching-compression actions. However, in all groups, for the elements whose b/t ratio takes a value greater than 5.5, the analyzed elements tend to acquire a non-ductile behavior. The punching effect of the core fades, in close connection with the increase in the value of this ratio. This phenomenon can easily be attributed to the increase in the characteristic Iy of the sections (geometric moment of inertia along the local axis y of the section).

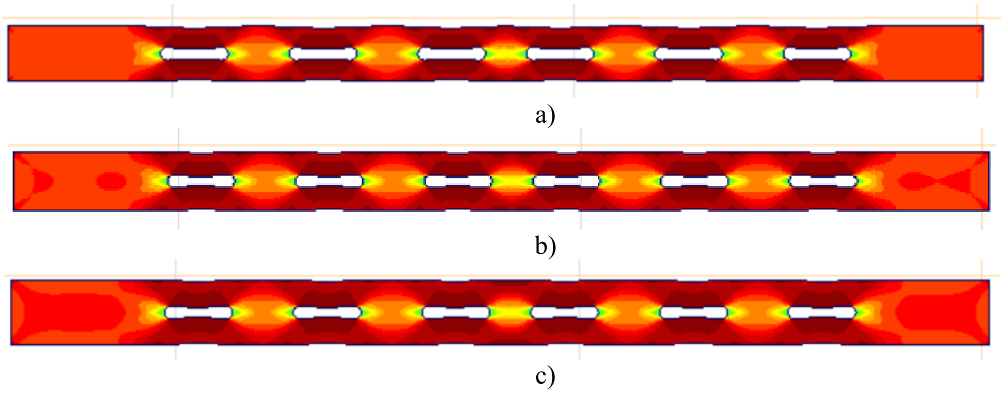


Figure 14. Stress distribution inside PCBRBs: a) PCBRB 8*50; b) PCBRB 8*56; c) PCBRB 8*625

From the results of the numerical analyses, regarding the reactions transmitted by PCBRB, the following conclusions can be mentioned:

- The displacement and deformation values directly influence the reaction values. The elements that show over-resistance to compression transmit lower reaction values, and the elements that develop greater deformations transmit reactions with higher values.
- The median areas of the active part, areas that, due to the induced deformations, lose contact with the support, do not transmit reactions to the support.

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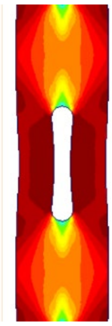
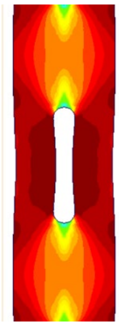


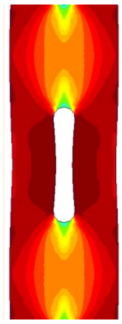
PCBRB 8*50
b/t 6.25
σ_{int} 341.32
ε_{int} 0.0010
σ_{ext} 317.83
ε_{Tmax} 0.0059

a)



PCBRB 8*56
b/t 7.03
σ_{int} 340.78
ε_{int} 0.0012
σ_{ext} 307.61
ε_{Tmax} 0.0064

b)



PCBRB 8*625
b/t 7.81
σ_{int} 340.24
ε_{int} 0.0022
σ_{ext} 300.14
ε_{Tmax} 0.0068

c)

Figure 15. Stress distribution in PCBRBs: a) PCBRB 8*50; b) PCBRB 8*56; c) PCBRB 8*625

5. Conclusions

Based on the present research and taking into consideration the objectives established in the second section of this paper, and the following initially imposed initial conditions:

- all analyzed elements, which are part of the same group, have the same sectional characteristics regarding the plastic active sectional area;
- all analyzed elements, regardless of the group they belong to, have the same active plastic length;
- all analyzed elements, regardless of the group they belong to, have the same maximum allowed displacement conditioned by the active plastic length;

one can conclude the followings:

- The geometric conformation of the section (b/t ratio) directly influences the character of PCBRB behavior under cyclic actions.
- The stiffness increase of the side wings perpendicular to the direction of action during the loading-unloading cycle and at the same time on the parallel direction to the direction of the degrees of freedom released by the presence of the gap leads to a non-ductile behavior, but up to a certain limit.
- The stiffness decrease in the same directions leads to a weighted increase in the ductile character of the behavior, but with the decrease in stiffness, the more significant occurrence of the local stability loss is observed for all the analyzed elements.
- The plastic length, or better said the length of the gap, becomes irrelevant outside of the values mentioned in the paragraphs above. For values of the b/t ratio greater than 5.5, a significant decrease in the ductile behavior is observed, while for values lower than 1.75, an increase in the same ductile behavior can be noticed, but local stability problems arise.
- The ratio (b/t) between the two slenderness ratios (L_y/L_x) assimilated with the two dimensions of the lateral wing geometry could be used in possible PCBRB pre-sizing stages.
- The value of the reactions transmitted by the PCBRB to the supports is directly influenced by the deformations and displacements, and the deformed areas, which lose contact with the supports, do not transmit reactions to the supports.

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