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Barrier for buildings: analysis of mechanical resistance requirements

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Abstract

Barriers (guardrails and balustrades) prevents people from falling, for example, from balcony, open windows and stairs. Barriers also retain, stop or guide person in buildings. To increase the transparency of these components, traditional materials such as bricks, wood and metal are being replaced by glass or an organic material, which has mechanical behavior different from traditional materials. Regulation usually specify some action to take into account in the design of barriers, but do not define the required resistance. There are no international standards (ISO or EN) to assess the fitness for use of barriers, only national standards, with different testing loading conditions and mechanical resistance requirements. In this paper is presented a comparison of requirements and experimental testing conditions specified in standards from Portugal, Spain, France, UK, USA and Brazil. The goal of this research is to find some equivalence between standards, regarding the mechanical resistance behavior of different materials (brittle/ductile materials) and set a worst case scenario as the basis for the guardrails mechanical resistance profile. Some relations between the service limits state (plasticity) of metal guardrails and maximum deflection are proposed.

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Keywords: GuardRails; Fatigue; Durability; Case Study; Experimental Techniques; Numerical Techniques

1. Introduction

In buildings balconies, terraces, landings, staircase are required elements to give people assess to higher floors or allow people to stay outside at higher levels. This architectural element requires protection to prevent people from

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falling. There are several types of barriers with different types of materials, fillings and fixings (UNE 85-237-91). For example, barriers mainly composed by metallic elements (aluminum, steel and stainless steel), glass, organic materials, wood, concrete or bricks.

To fulfill with safety requirements barriers should comply with requirements related to the minimum height of protection, with maximum openings size and that its components are not easily scalable. The barriers must withstand accidental or involuntary type of actions and their flexibility should be limited to prevent alarming users (BS 6180). Usually the barriers aren't designed to prevent that people can transpose it intentionally, nor are they designed to withstand acts of vandalism.

The assessment of barriers safety could be based on ultimate limit state and serviceability limit state (RSA). The ultimate limit state (ULS) are associated with severe damage, for example, breakage, excessive deformation, instability, cracking and plastic deformation. The serviceability limit states (SLS) are associated with some severe losses, eg not compatible deformation in service conditions, presence of plastic deformation or cracking. The barriers not being a structural element are subject to particular specifications, whose actions are based on static loads specified in codes (RSA and EN 1991) and dynamic loads detailed in technical specification for guardrails, for example BS 6180, NBR 14718, NF-P 01-013, NP 4491, UNE 85-238-91. The technical specifications for the qualification of guardrails typically involve the following characteristic:

- Dimensional characteristics;
- Resistance to horizontal static force (deformation and safety tests);
- Resistance to vertical static force;
- Resistance to dynamic test shock with soft body;
- Resistance to dynamic test shock with hard body;
- Resistance to wind load
- Evaluation of the durability of materials and coatings.

In section 2 is presented a comparison of requirements for guardrails in different technical specification. In section 3 is presented a theoretical and experimental analysis to set limits to obtain the same stiffness for barriers, supported in traditional barriers of steel. In section 4 are presented the main conclusions.

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Nomenclature

δ	Deformation (mm)
σ	Stress (Pa)
σ_y	Yield stress (Pa)
E	Elastic modulus (Pa)
H	Height (m),
I	Inertia moment (m^4)
L	Width (m)
M	Bending moment (N.m)
P	Punctual load (N)
SLS	Serviceability limit state
ULS	Ultimate limit state
w	Linear load (N/m)
x	Distance from the top of posts (m)
y	Distance from the neutral fibre (m)

2. Comparison of requirements for mechanical resistance of guardrails and balustrades

2.1. Comparisons of different standards

As detailed previously, there are no international standard for the assessment of guardrail performance despite their importance for the use and safety of buildings. The design and assessment of this building component is done supported by regulation and national standards. In table 1 and 2 are summarized the technical specifications, the proposed actions and loads and the requirements in Portugal (NP standard), France (NF standard and CSTB for guardrail with glass), Spain (UNE standard), UK (BS standard), USA (ASTM – standard) and Brazil (NBR-standard).

Table 1. Requirements of mechanical resistance for guardrails

Technical specification	Action	Requirements
NP 4491	**Horizontal static load test (SLS):** Dwellings: 0,5 kN/m* Services: 0,7 kN/m* Public: 1,0 kN/m* Crowd: 3,0 kN/m* **Horizontal static load test** (ULS): 1.5 x ELS** **Vertical static load**: 1 kN/m** **Impact, hard body**: 3.75 J*** **Impact, soft body**: 600 J***	**Horizontal static load test (SLS):** Residual deformation not greater than: - 1 mm for metallic guard rails; - 3 mm for guardrail of other material. Do not present stability and robustness problems **Horizontal static load test (ULS):** Guardrail with posts: residual deformation ≤ A/125 Guardrail with lateral anchorage: residual deformation ≤ L/125 Remain stable. **Vertical static load:** Residual deformation ≤ 1 mm for metallic barriers and 3 mm for barrier of other materials. **Impact test:** no fall of debris that could harm persons
NF P 01-013	**Horizontal static load test (SLS):** Dwellings: W≤3,5 m:1,3 kN* W>3,5 m: 0,4 kN/m* Public: 1 kN/m* Stadiums: 1,7 kN/m * **Horizontal static load test** (ULS): 1.5 x SLS for steel guardrails** 1.7 x SLS for aluminium guardrails** **Vertical static load**: 1 kN **Impact, hard body**: 3.75 J*** **Impact, soft body**: 600 J***	**Horizontal static load test (SLS):** Residual deformation not greater than: - 1 mm for metallic guard rails; - 3 mm for guardrail of other material. Do not present stability and robustness problems. **Horizontal static load test (ULS):** Metallic guardrails: Residual deformation not greater than: - $\delta/h \leq 1/125$ if $\sigma \leq 1.1\sigma_y$ (without plastic deformation) - $\delta/h \leq 1/125 \times 1.1\sigma_y/\sigma$ if $\sigma \leq 1.3\sigma_y$ (with plastic deformation) Wood guardrails, 3 tests until rupture: - Lower ultimate strength /2.2 ≥ SLS - Average ultimate strength/2.5 ≥ SLS **Vertical static load:** Residual deformation≤3 mm **Impact test:** no fall of debris that could harm persons
CSTB	Same as NF P 01-013, except that for horizontal static load the load for ULS the triple of ULS defined in NF **Wind load test** **Impact test, hard body:** 3 e 10 J. **Impact test, soft body:** 700 e 900 J:	**Horizontal Load test (SLS):** Maximum deformation of 35 mm and residual deformation not greater than 3 mm, **Horizontal Load test (ULS):** No rupture or collapse of guardrail. Others same as NF.
UNE 85-238-91	**Horizontal static load test (SLS):** Dwellings: L≤3,5 m:1,3 kN* L>3,5 m: 0,4 kN/m* Public: 1 kN/m* **Horizontal static load test (ULS):** 1.5 x SLS for steel guardrails** 1.7 x SLS for aluminium guardrails** **Vertical static load**: 1 kN** **Impact, hard body**: 3.75 J*** **Impact, soft body**: 600 J***	**Horizontal static load test (SLS):** Residual deformation not greater than: - 1 mm guardrail ferrous material. - 3 mm guardrail of other material. Do not present stability and robustness problems **Horizontal static load test (ULS):** Metallic guardrails, Residual deformation not greater than: - $\delta/h \leq 1/125$ se $\sigma \leq 1.1\sigma_y$ (without plastic deformation) - $\delta/h \leq 1/125 \times 1.1\sigma_y/\sigma$ se $\sigma \leq 1.3\sigma_y$ (with plastic deformation) Wood guardrails, 3 tests until rupture: - Lower value of ultimate strength /2.2 ≥ SLS - Average ultimate strength/2.5 ≥ SLS **Vertical static load:** Residual deformation≤3 mm **Impact test:** no fall of debris that could harm persons
BS 6180	**Horizontal static load:** Class 1: 0,36kN/m e 0.5kN/m^2; 0.25kN$^+$ Class 2: 0,74kN/m e 1.0kN/m^2; 0.5kN$^+$ Class 3: 1,5kN/m e 1.5kN/m^2; 1.5kN$^+$ Class 4: 3,0kN/m e 1.5kN/m^2; 1.5kN$^+$ Wind load resistance **Impact test (barrier with glass or organic materials):** free path 0,6m to 1,5 m, class C free path >1,5 m, class A	**Horizontal static load:** Maximum deformation should not exceed the maximum deflection limits of material or 25 mm^{++}, whichever is the smaller. The infill should also have a deformation less than L/65. L is the longest dimension of the glass. Resistance stress higher than tensile stress. Fixing system should be designed with 1.5 the testing load of guardrail. In barriers with glass use a safety factor of 4 for glass resistance.

* Load during 3 minutes; ** Load during 15 minutes; *** impact in the middle of infill element; + the design load should be the most onerous arising from the distributed and point load in the infill, ++ relative to its original position.

Table 2. Requirements of mechanical resistance for guardrails

Technical specification	Action	Requirements
CUAP	**Horizontal static load:** value according EN 1991-1-1 for SLS and ULS. **Vertical static load:** 1 kN **Impact, soft body:** 350 J (EN 12600) **Wind resistance:** EN 1991	**Horizontal static load (SLS):** deformation ≤1/100 H; residual deformations≤1 mm for steel and ≤3 mm for other materials. **Horizontal static load (ULS):** no rupture. **Impact of soft body:** no collapse, no pendulum penetration or projection of fragments. **Wind load resistance:** same as horizontal load
ASTM E985 Classification for metallic barriers E894 Testing of fixings E935 Testing of metallic barriers E2353 e E2358 Glass barriers D7032- Wood and organic barriers	**Concentrated load:** 890 N; 1330 N; 1620 N. **Distributed load on top**: 730N/m, 880N/m. It is done a test with point load and after with distributed load with horizontal direction and after with vertical direction. **Impact test in glass barriers:** 545 J	**Horizontal deformation:** Concentrated load applied in the top of post: deformation ≤H/12 Horizontal deformation: application of load in the middle of rail: ≤ H/24 + L/96 **Vertical deformation:** application of load in the middle of rail: ≤L/96 **Residual deformation** ≤ 20% of maximum allowed deformation.
NBR 14718	**Horizontal static load (SLS):** dwellings 400 N/m, public 1000 N/m**; **Horizontal static load (ULS):** 1.7xSLS load* **Vertical static load:** same value as the horizontal static load for ULS** **Impact soft body:** 600 J***	**Horizontal static load (SLS):** Deformation with preload ≤ 7 mm; deformation with SLS load ≤ 20 mm and residual deformation ≤ 3mm. Do not present stability and robustness problems **Horizontal static load (ULS):** Deformation with load ≤ 150 mm. **Vertical load:** Do not present stability and robustness problems. Deformation ≤20 mm, residual deformation ≤8 mm. **Impact load:** No cracks and openings in the barriers, No detachments from infill that could harm persons.

* Load during 3 minutes; ** Load during 15 minutes; *** impact in the middle of infill element; + the design load should be the most onerous arising from the distributed and point load in the infill, ++ relative of its fixings.

As shown in table 2, there are no uniform way to assess the fitness for use of barriers. There are common understanding about requirements, but not about load levels and acceptance criteria. For examples, almost all standards have requirements about resistance to horizontal static load, but not about the types of load (punctual, distributed), the value (range between 0.36 kN/m to 0.73 kN/m for dwellings for serviceability limit state - SLS) and the acceptance criteria about maximum deflection is also very different, in some cases there are only criteria for residual deformation and in other cases there are also requirements for the maximum deformation when loaded. Since in the elastic domain the deformation is proportional to the load at the top of the barriers, the load and deformation acceptance criteria (table 1 and 2) show that there are no uniform criteria for the maximum deflection for glass barriers between CSTB that allows a deformation of 35 mm, British Standard 25 mm and Brazilian standard 20 mm, for almost the same loads (0.4 kN/m). For metallic barrier, usually its note specified a maximum deformation with load, but only a residual deformation (NP 4491, UNE 85-238-91, NF P 01-013).

In the next section it's developed a numerical study of the elasto-plastic behavior of metallic barrier to estimate the maximum deflection and assess the order of magnitude to impose maximum deflection limits for barriers of other materials, such as glass or organic material, to prevent alarm of building users due to excessive flexibility of barriers; because a limit of 20 mm is quite different of 35 mm.

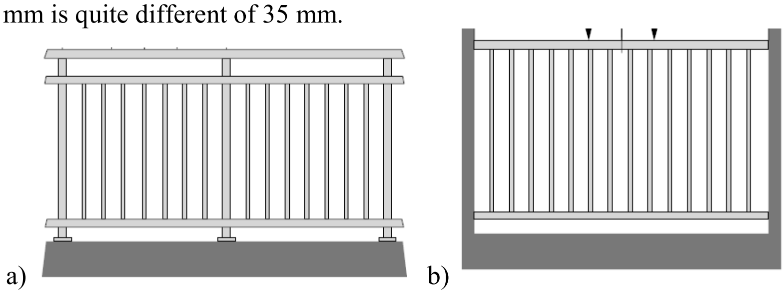


Fig. 1. a) guardrail with posts; b) guardrail without posts and with lateral fixing.

3. Maximum deformation for barriers in horizontal static load test

3.1. Estimations of maximum horizontal deformation with horizontal static load in metal barriers

For traditional metal barrier the standard UNE 85-239-91 specifies the posts characteristics to comply with Spanish testing standard UNE 85-238-91, that define requirements for residual deformations and doesn't define limits for the maximum deformation. Assuming that barriers are well fixed, the maximum deformation of barrier (posts/rails) can be estimated using the deformation for a cantilever beam for posts (fig. 1a, eq. 1) and simple supported beam for barriers without posts and with lateral fixations (fig 1b, eq. 2), Beer. Analyzing the maximum deformation of 32 steel posts of rectangular cross section (fig 2a), with 0.6, 0.8, 1.0 e 1.1 m height (H), spaced (L) 1.0, 1.5, 2.0 and 2.5 m and for loads of 0.5kN/m and 1.0kN/m, the average maximum deflection is (δ/H) nearly 1/200, with a maximum of 1/120 and several cases with values lower than 1/400. For other cross section (square or round) the deflection is similar. In barriers without posts and with lateral fixation, the analysis of 32 cases with steel rails of rectangular, square, round and bar cross-section, with span (L) of 1.0, 1.5, 2.0 e 2.5 m, loads of 0.5 kN/m and 1.0 kN/m gives an average maximum deflection of (δ/L) 1/300, figure 2b. The maximum value is 1/185 and there are several cases with values lower than 1/500.

$$\delta = \frac{PL^3}{3.E.I} \tag{1}$$

$$\delta = \frac{5wL^4}{384.E.I} \tag{2}$$

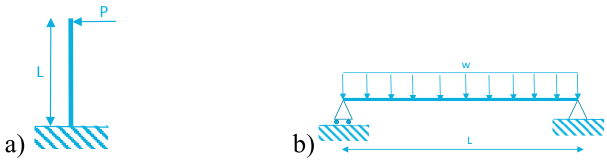


Fig. 2. a) Model for barrier with posts; b) Model for barrier without posts and with lateral fixing.

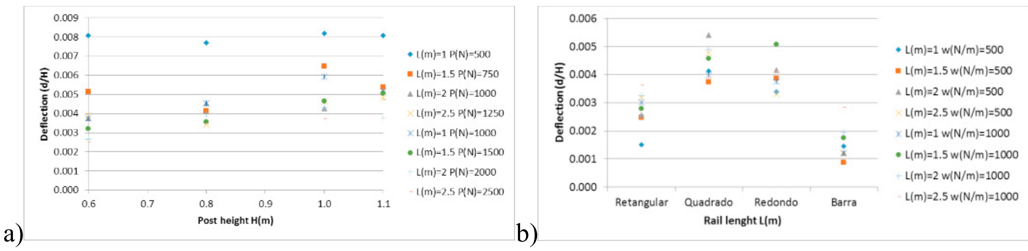


Fig. 3. (a) Maximum deflection of steel posts of rectangular cross section UNE 85-239-91; (b) Maximum deflection of steel rail for barrier without posts and with lateral fixation UNE 85-239-91

3.2. Analysis of plastic deformation of resistant elements of barriers

3.2.1. Theoretical model

The residual deformation of barriers may be derived from insufficient mechanical strength of joints and connections or the yielding of resistant elements. To maximize the allowable deformation of resistant elements of barriers it is assumed that the connections are sufficiently rigid and that the residual strains are derived essentially from plastic deformation of posts or rails. From section 3.1 we conclude that posts have higher deformation than rails, and in this section the study will be detailed only for posts, the most critical elements. In the stress analysis, the behaviour of posts will be study has a cantilever beam with a bending moment (M) on the top, given by P.L (fig.

4a). In the post cross section, the stress varies with the distance to the neutral fiber (y, eq. 3) in the case of small displacements and it takes the maximum value along the surface (y=c). If the bending moment exceed the maximum elastic moment M_y (eq. 4) yield occurs.

As the bending moment on the post changes with distance from the top (x), the post plastic section could change with that distance (Fig. 4a, eq. 5). In the analysis it is considered that the post material has an elasto-plastic behaviour (fig. 4b) with the properties for steel: σ_y=250 MPa and E=200 GPa. When the moment equals the elastic limit ($M=M_y$, Fig. 5) yield occur along the surface. As the moment increase ($M>M_y$) the plastic zone increase and the thickness of the elastic core (y_y) can be obtained by eq. 6. In the plastic zone ($y \geq y_y$) is installed the yield stress (σ_y), while in the elastic core zone the linear model apply (eq. 7). In this case the radius of beam curvature can be obtained by eq. 8.

When the load is removed, the stress and strain decrease linearly and residual stress are installed (fig 6). The residual stress can be obtained using the superposition method (eq 9, fig 6). The beam curvature can be calculated by eq. 10, because Hook's law remains valid for the elastic zone ($y<y_y$). Because the bending moment change with the distance from the bottom of post, the residual deformation at the top of the post need to be calculated integrating the deformation and rotation along the post height. The deformation associated to the bending due to residual stress can be calculated using eq 11, the rotation by eq 12 and the deformation by eq 13. The residual deformation due to beam rotation by residual stress can be calculated using eq. 14.

$$\square = \frac{M(x).y}{I} \quad (3)$$

$$M_y = \frac{\square_y.I}{c} \quad (4)$$

$$x_y = \frac{\square_y.I}{c.P} \quad (5)$$

$$y_y = \frac{\square_y.I}{M(x)} \quad (6)$$

$$\square = \frac{\square_y}{y_y} y \quad (7)$$

$$\square = \frac{y_y}{\square_y} = \frac{y_y.E}{\square_y} \quad (8)$$

$$\square_m = \frac{\square_y}{y_y} c \quad (9)$$

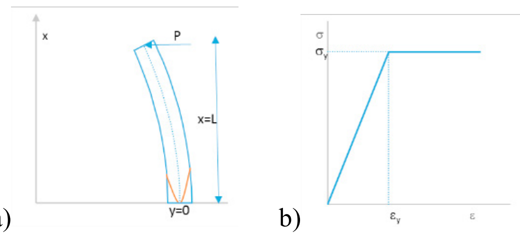
$$\square = \frac{y_y}{\square_{y'}} = \frac{y_y.E}{\square_{y'}} \quad (10)$$

$$\square = \frac{d^2y}{dx^2} = \frac{M(x)}{E.I} \quad (11)$$

$$E.I.\square(x_y) = \square_o^{x_y} M(x)dx + c_1 \quad (12)$$

$$E.I.\square(x_y) = \square_o^{x_y}\square_o^{x_y} M(x)dx + c_1 x + c_2 \quad (13)$$

$$\square = (H \square x_y)\sin(\square(x_y)) \quad (14)$$



a) b)

Fig. 4. a) Bending of post; b) elasto-plastic behaviour

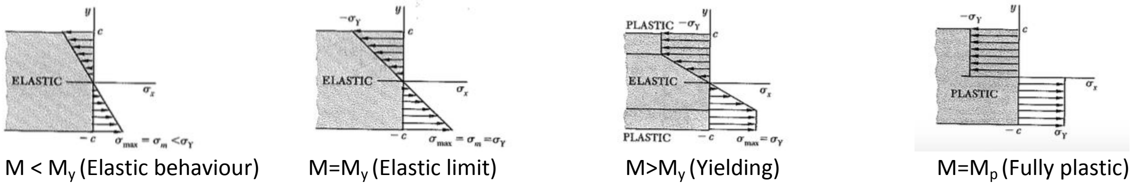


Fig. 5. Bending stress distribution (Beer et al.)

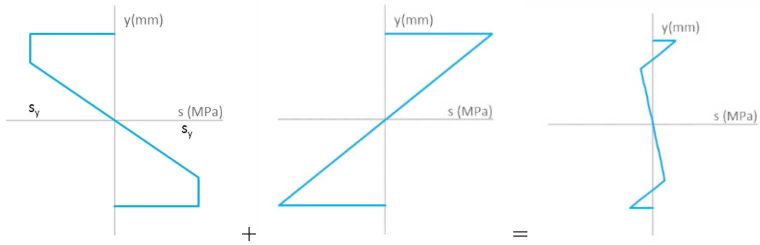


Fig. 6 – Application of superposition to calculate residual stress

3.3. Relation between maximum deflection and the residual deformation in steel posts

With the theoretical model developed in the previous section it was assessed the maximum load to obtain the residual deformation of 1 mm in a tubular profile with 2 mm thick wall for the serviceability limit state (ELS) and 1/125 for the ultimate limit state (ULS = 1.5x ELS). This calculation was performed for guards with a distance between posts of 1.0 m, 1.5 m, 2.0 m 2.5 m, with a load of (w_{SLS}) 0.5 kN/m and 1.0 kN/m. The results are in Fig. 7a and 7b, for the two loads, for posts with square cross-section (h/b=1) and for posts with rectangular cross-section with h/b of 0.5, 2 and 4. The results show that in the absence of other weak points in barriers, the residual deformation criteria in metal barriers allows a maximum deformation above 1/75. The deformation limit to prevent residual strain depends on the distance between posts and the ratio between the sides of the post section (h/b). The limit decrease as h/b increase and the distance between posts increase. For posts 2 m apart, 1.1 high of square cross-section and h/b of 4, the most permissible requirement (w=0.5 kN/m, square) gives 1/40 and maximum deformation of 30 mm and the most stringent (w=1.0 kN/m, h/b=4) gives 1/70 and 16 mm maximum deformation. For posts according UNE 85-239-91, the maximum deformations are about 1/200 (see section 3.1). Using the elastic behaviour relation, the tension in posts satisfying 1/200 deformation can be calculated by eq. (15). To have stress higher than yield strength in steel posts it is required a distance from the neutral fibre larger than 92 mm, which clearly exceeds the specified sizes in UNE 85-239-91, indicating that it is unlikely to occur yield in those posts.

$$\square = \frac{1}{200}\frac{3.c.E}{H} \qquad (15)$$

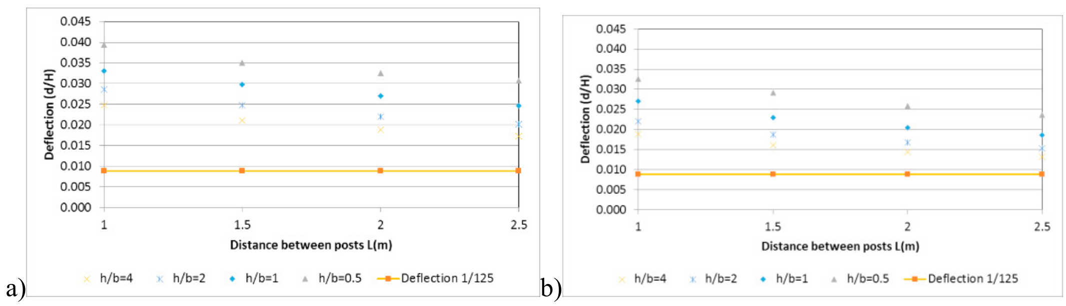


Figure 7 Maximum deformation of posts to prevent excessive residual deformation. (a) SLS=0.5 kN/m; (b) SLS=1.0 kN/m

3.4. Testing

It was carried out the horizontal static loading test in a barrier with posts 1 m high, spaced 1 m, rectangular cross section with h/b=2 and load of 1.0 kN/m. In this test it was measured a maximum deformation of 21.4 mm (d/H=0.021) with a residual deformation of 1.05 mm. From figure 7b, the calculated maximum deflection for L=1 and h/b=2 is 22 mm, indicating that the previous calculation agrees with this test result.

4. Conclusions

There are several national technical specifications to assess the fitness for use of building barriers, which present different loads and requirements, as shown in tables 1 and 2. Regarding barriers flexibility to static horizontal loads, the requirements usually change with barrier type and material. In some cases, there are requirements for maximum deformation (ranging from 20 mm to 35 mm) and in others only limits to the residual deformation. To assess the equivalence between stiffness requirements of metal barriers stated by maximum deformation and residual deformation, it was developed a theoretical study of mechanical behaviour of posts. The main finding was that to prevent excessive residual deformation, the maximum deformation of posts should be limited to 1/75 for barriers with 1.1 m high and posts 2.5 m apart. This limit (1/75) is close to the limit specified in CUAP and BS 6180 for infill, but it is too strict compared to the allowed maximum deformation of 20 mm in NBR 14718 or 25 mm in BS 6180, but less restrictive than the predefined solutions defined in UNE 85-239-91. This limit of deformation could be as high as 1/25 for barrier with posts spaced 1 m, load of 0.5 kN/m and cross section h/b=0.5. This value (1/25) is similar to the limits specified in ASTM standards, but ASTM specifies a higher load (0.73 kN/m). The average of all values in figure 7a and 7b provides a limit of 1/45 or 25 mm.

To keep the same feeling of robustness of steel barriers, a deformation limit should be specified for the horizontal static test (serviceability limit state). From the analysis presented in this paper, the average value of 1/45 or 25 mm could be acceptable, feasible and in line with some recent standard (NBR 14718, BS 6180). To assess the fitness for use other tests should be done as mentioned in table 1 and 2, namely horizontal static test (ultimate limit state, residual deformation ≤1/125), vertical load (residual deformation ≤ 3 mm other materials) and impact test.

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