“Study of Temporary Edge Protection Systems (TEPS) class A manufactured of steel tubes”

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ABSTRACT

One of the most effective measures to control the risk of fall from heights is the use of temporary edge protection systems. (TEPS)

In Europe, the UNE-EN 13374 standard "Temporary edge protection systems. Product specification, test methods" specifies the requirements to be met by these systems and the assessing methods to verify their compliance.

In this paper, three TEPS pipes made of steel have been analytically and experimentally evaluated and the necessary dimensions to meet the standard requirements have been obtained.

Keywords

Prevention, steel guardrails, evaluation methods, fall protection, construction sites.

INTRODUCTION

In the construction sector, accidents produced by height falls have proved to be a high percentage of all accidents occurred (OSHA, 1990; Instituto Nacional de Seguridad e Higiene en el Trabajo, 2007; SESS, 1999). Both nationally and internatiobally, the standards and regulations limit the height of the fall (Real Decreto 1627/1997, 1997; IV Convenio General del Sector de la Construcción 2007-2011, 2007; OSHA. Part 1926 Subpart M CFR 1926.500, 1998; Québec Safety Code for the Construction Industry, 2001).

In order to prevent the risk of height falls, the strategy to be followed (OPPBTP. Mémo-practique B1 M 01 94, 1994; Law 31/1995, 1995) refers firstly to the need to eliminate risk at the origin, through the construction work planning, integrating the protection within the structure or installing collective protections to avoid falls. If this is not possible, the height fall is limited using collective protections, which are normally systems formed by nets transmitting the impact energy to the construction structure through more rigid elements, mainly of metal.

Many of these protection systems are standardized (UNE-EN 1263-1, 1997; UNE-EN 1263-2, 1998) in Europe. In Spain, the system of jib nets has been used for many decades, even when main aspects of its performance, such as the maximum speed experimented by the body after the impact on the net have not been known until recent studies have been carried out (Irles, et. al, 2002; Segovia, et. al, 2007). If by using these two steps the risk has not been avoided then individual protection systems are used against workers' falling. In this case, as the systems need to be fixed to the structure, it is important to know the pull out strength of the anchor at the fixing point (García, et. al, 2008; UNE-EN 795, 1997; UNE-EN 795/A1, 2001).

The use of temporary edge protection systems (TEPS) as protection against falling height represents an efficient system which eliminates the risk at the origin, avoiding the fall and preventing the possibility of suffering damages when a worker impacts against a system which only limits the fall height.

In the literature and documentation regulating the TEPS studied (eLCOSH, 2001; OPPBTP. Mémo-practique B1 F 01 93, 1993; ASTM E 985-87, 1987) these devices have to exceed some geometric and mechanical requirements. The geometric requirements establish the TEPS dimension so that the worker does not go beyond the system and fall, or that objects do not pass from the slab to the vacuum. The mechanical requirements demand a specific system strength and limit the displacements regarding certain loads.

Spanish standards addressed the prevention of height falls in a general way until 2004 when the UNE-EN 13374 standard was published. This standard specifies the requirements --both geometrical and mechanical—which TEPS used in construction works or in building or structure maintenance should exceed, depending on whether they belong to class A, B or C. Class is determined considering the working surface inclination and the fall height of the person to protect. If systems comply with this standard, they grant that they are suitable since they have the proper strength and performance.

The most widely used Systems are class A ones, used when the inclination angle of the working surface is less the 10º (González & Cobo, 2006). Class B ones are used with working surface inclinations in between 10 and 30º and up to 60º for falling heights smaller than 2 metres. Class C is suitable for inclinations in between 30 and 45º or up to 60º is the falling height is smaller than 5 meters.

The actual problem in Spain is that most of the TEPS used in construction works have not been assessed and therefore their mechanical behaviour is unknown.

ASSESSMENT TECHNIQUES OF CLASS A TEPS

Types of analysis

UNE-EN 13374 standard allows performing an analytical and experimental assessment in order to verify the mechanical requirements. Both procedures are further described according to the standard.

Analytical procedure

Calculations have to be carried out following the Limit State method, using the European standards for the structure engineering. For steel elements, ENV 1993-1-1 – Eurocode 3 (1993) has been followed.

Three situations have been analyzed: Ultimate Limit State (ULS), Service Limit State (SLS) and accidental load.

For ULS, edge protection systems and each of the components, except the toeboard, have to be designed to support a FH1 = 0.30 kN load applied perpendicularly to the post axis. The toeboards shall be capable of supporting a FH2 = 0.20 kN load. These loads should be applied at the two most unfavourable points. When this requirement is fulfilled, it is implies that MSd ≤ MRd where MSd is the flexural moment acting on the studied section and MRd is the moment capable of resisting the section.

At the limit state, an γF action increase coefficient of 1.5 should be used, and a decrease factor of the material strength γM of 1.1 for metal elements.

To meet the SLS standard, the deflection of the whole system to which the FT1 of 0.30 kN load is applied should be greater than 55 mm. For the toeboard, the load to be applied FT2 is of 0.20 kN.

Regarding the study of accidental loads, the standards say that the principal guardrail, the intermediate guardrail and the toeboard should support a gravitatory precise strength of FD = 1.25 kN. This load should be applied in the most unfavourable position of the TEPS, at a 10º inclined sector from the vertical. Compliance of this requirement should be established as in the analogous case of the ULS.

For the assessment of SLS and the accidental loads, the action increase coefficients and the strength decrease coefficients of the materials take the unit value.

Experimental procedure

Testing of SLS and ULS is done applying horizontal actions according to the load cycle further explained. Firstly, an initial load of 0.10 kN is applied to the system. This load is maintained for a minute, and after, the system is unloaded, leaving the residual displacement forming the δ_1 reference deflection. Later, the load of the corresponding test is applied, keeping it for one minute and then unloading it.

Testing of SLS

The maximum load for this test, $Q_{K,}$ is of 0.30 kN for the guardrails and the post, and of 0.20 kN for the toeboard, applied at five regular increments. Once the load has been reached, it should be maintained for one minute so that the fluency characteristics of the system can be determined.

Maximum horizontal displacement experienced by the system for a deflection which should not surpass the 55 mm value.

Testing of ULS

The maximum testing load $F_{máx.}$ is obtained by $F_{máx.} = \gamma_F \cdot \gamma_M \cdot Q_K$, where γ_F and γ_M are the partial safety coefficients for ULS (action increase and material strength decrease respectively) and Q_K is the characteristic load depending on the element considered. It should be applied at regular increments and should be maintained for a minute. Deflection of the toeboard $\delta_{máx}$ needs to be measure under the maximum load.

The test load should be removed and the residual deflection δ_{res} measured. After it, the system needs to be loaded with an identical load scheme, increasing the fracture load R_u causing a notable failure to the system or to the element forming it.

Deflection at the reference position $\delta_{1,}$ should be registered, as well as the deflection under the maximum load $\delta_{máx}$, the residual deflection δ_{res}, and the ultimate load R_u.

Test is considered valid when three conditions occur simultaneously: no plastifications occur under the maximum load, the residual deflection is smaller than 10% of the deflection under the maximum load, and R_u is higher than 1.2 times the maximum testing load.

Testing of accidental load

A vertical downward load of 1.25 kN should be applied at the most unfavourable point of TEPS and testing that the system can support it should be ensured.

EXPERIMENTAL WORK PERFORMED

Characteristics of the Systems analyzed

The goal of this study has been to assess the performance of class A TEPS commonly used in construction works. For it, the UNE-EN 13374 standard has been used as reference.

Three SSPB have been analyzed with a span between the posts of 2400 mm and a height of 1000 mm, measured from the reference level up to the upper edge of the principal guardrail. The principal and intermediate guardrails and the post have been manufactures with S235 steel tube.

The post hinges are of S275 steel. The telescopic toeboard has been manufactured in cold rolled steel.

Table 1 shows the geometrical characteristics of the three systems.

Table 1. Geometrical characteristics of the three systems studied.

	SYSTEM 1 (S1)	SYSTEM 2 (S2)	SYSTEM 3 (S3)
GUARDRAILS	○ 25 · 1.5 mm	○ 40 · 1.5 mm	○ 40 · 2 mm
POSTS	○ 40 · 1.5 mm	□ 35 · 1.5 mm	○ 40 · 2 mm
TOEBOARD	telescopic, manufactured in cold rolled steel		

The three systems have been anchored to a reinforced concrete beam in which three PVC pipes have been embedded to host both the squared section post of side 35 mm, and the circular section posts 40 mm in diameter. Figure 1 shows, as an example, the placement and geometrical characteristics of system 3.

The dimensions of the first analyzed system are the ones commonly used for slab Edge protection on the construction work sites in Spain. The second one is used only in exceptional circumstances. The dimensions of the third system have been determined after the calculations referred on the UNE-EN 13374 standard.

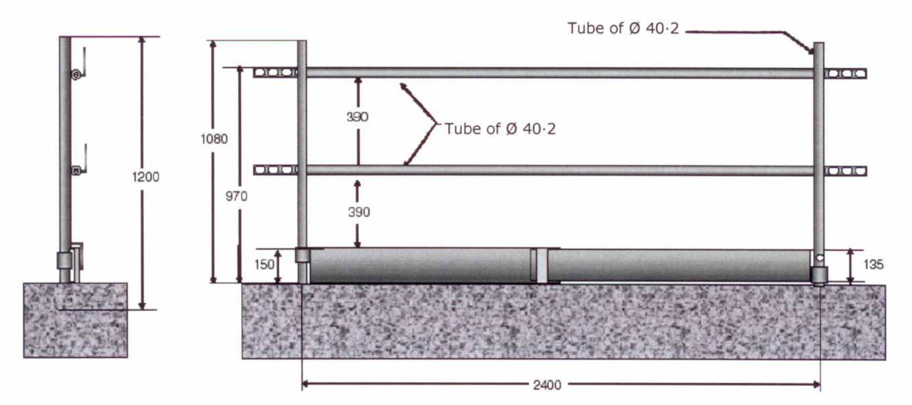


Figure 1. Geometrical characteristics of system 3.

Algebraic analysis procedure

The calculation model adopted for the analytical assessment are the following: the guardrails have been considered as beams resting on two points, being the supporting points the intersection with the posts; the post has been considered as a bracket fitted in the slab.

For the calculation of the system, elements have been separately studied incorporating for the analysis of each one of them the effects produced by the others.

The analysis in ULS is identical for the principal and intermediate guardrail. The most unfavourable situation for these elements is produced when the load is placed at the centre of the guardrail, resulting in the maximum deflecting moment of the bar.

For the post, the most unfavourable situation is produced when the load is applied on its cantilevered edge and the most unfavourable section is the base, where the maximum deflection moment and the maximum shear stress is produced (figure 2).

For the calculations in SLS the horizontal movement of the system has been obtained as the addition of the guardrail deflection loaded at the centre of the span and the post deflection. Deflection at the post has been calculated with an action which is half the guardrail load and applied on the edge (figure 3). It has been proved that the deflection at the principal guardrail is greater than the deflection at the intermediate one.

The calculation for accidental actions at the guardrail follows the same methodology as the calculation process in ULS, applying a vertical load of 1.25 kN at the most unfavourable position and using as increase coefficients or decrease coefficients of material strength the unit value.

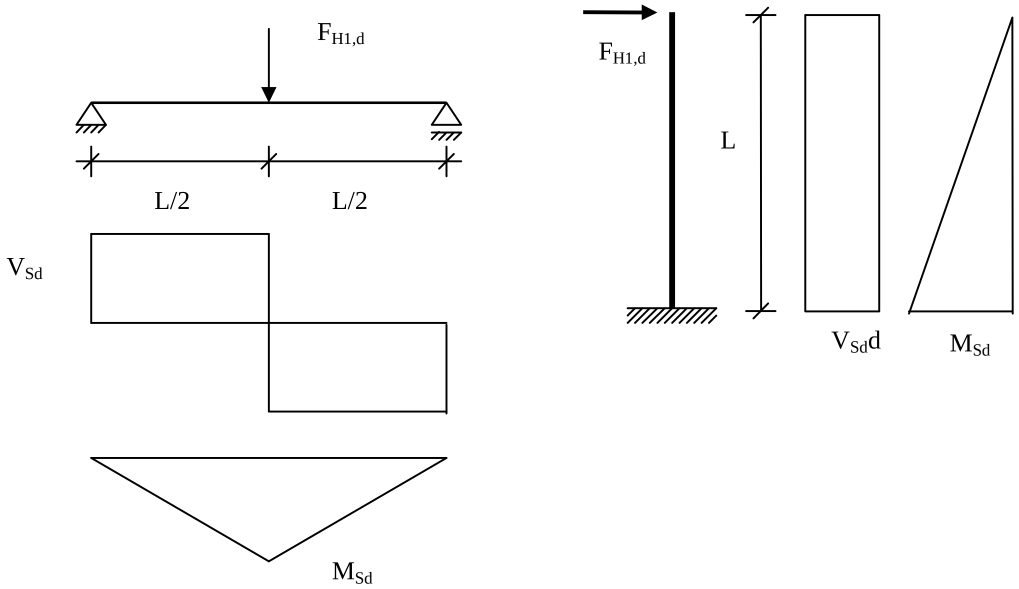


Figure 2. Calculation model for the guardrails and the post.

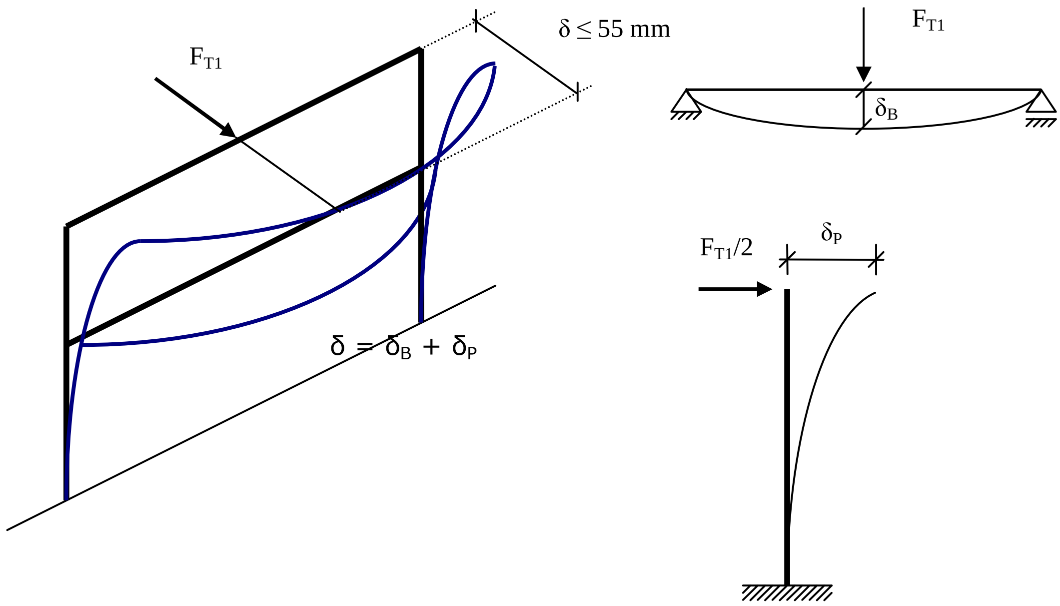
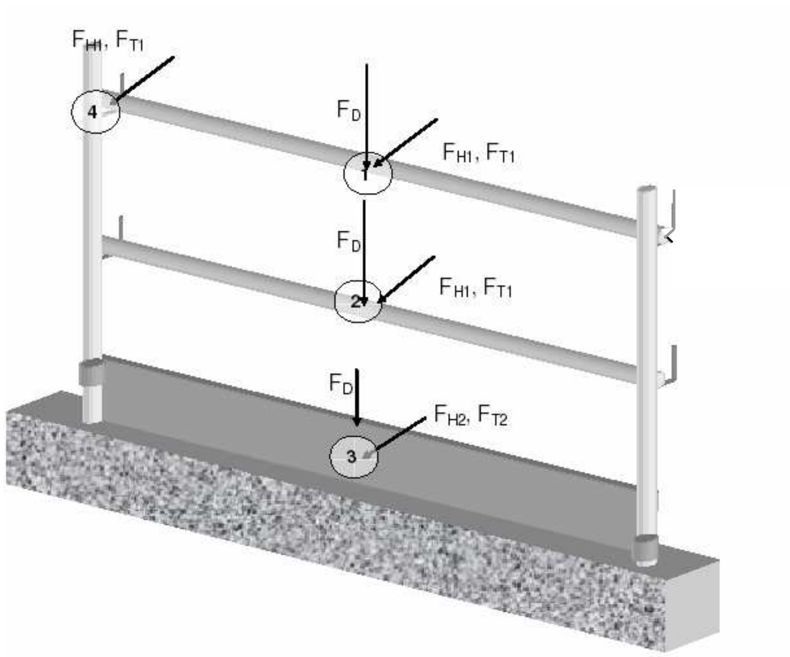


Figure 3. Calculating the system deflection.

Experimental analysis procedure

All tests have been performed at the premises and with the facilities supplied by the Laboratorio de Elementos de Seguridad del Instituto Tecnológico de la Construcción (AIDICO). A test frame has been used with two load actuators, one for horizontal load applications and another one for the vertical loads. The movements have been obtained using a movement transducer. A control system and one for obtaining data through specific software has recorded the load data and the displacements in each of the tests.

For each of the TEPS tests, the load cycles are applied in the most unfavourable points of the system, selected by normative criteria and from the research group (figure 4).



F_{T1}: Force applied to meet deflection requirement (applied on points 1, 2 and 4)
F_{T2}: Force applied to meet deflection requirement (applied on point 3)
F_{H1}: Force applied to meet strength requirement (applied on points 1, 2 and 4)
F_{H2}: Force applied to meet strength requirement (applied on point 3)
F_D: Accidental loading (vertical)

Figure 4. TEPS test arrangement in accordance with UNE-EN 13374.

The load applied on points 1, 2 and 3, situated at the centre of the upper and lower guardrails and at the toeboard produce a maximum flexural moment in these elements (strength requirements an accidental loading) and the maximum displacement of the system (deflection requirement). Point 4, situated at the edge of the post, produces the maximum flexural moment and the maximum post displacement.

In TEPS made of metal tubes, it is not necessary to check the section next to resting points of the horizontal elements of the post. The application of a load on this section would cause the maximum shear stress, of approximately the load value, but the bending or flexural checking results as most unfavourable.

RESULTS OBTAINED

Table 2 shows the results obtained for the deflection and strength tests performed for the three systems studied when the loads were applied on the principal guardrail (point 1), the toeboard (point 2) and the upper part of the post (point 4). It also includes the analytical results corresponding to the strength checking. The data of the intermediate guardrail (point 2) are not registered, since they are less favourable than those of the principal guardrail.

Table 2. Deflection experimental results and comparison between the analytical and experimental results for the strength testing.

Element	System	Deflection		Strength					
		Experimental		Experimental				Analytical	
		F_{T1} /F_{T2} (kN)	δ (mm)	F_{H1}/F_{H2} (kN)	R_u (kN)	$δ_{máx}$ (mm)	$δ_{res}$ (mm)	M_{Sd} (kN·m)	M_{Rd} (kN·m)
Principal guardrail	S1	0.30	66.67	0.50	0.57	138.24	30.27	0.27	0.18
	S2	0.30	28.87	0.50	1.34	46.69	3.17	0.27	0.48
	S3	0.30	21.66	0.50	1.94	37.20	1.20	0.27	0.62
Post	S1	0.30	20.98	0.50	1.08	28.62	1.60	0.45	0.48
	S2	0.30	19.48	0.50	0.82	34.12	6.25	0.45	0.54
	S3	0.30	14.97	0.50	1.41	23.15	1.32	0.45	0.62
Toeboard	S1, S2, S3	0.20	13.43	0.35	0.63	30.18	2.25		

Figures 5 and 6 show the results of the deflection tests when the load is applied on the central point of the principal guardrail (figure 5) and on the edge of the post (figure 6).

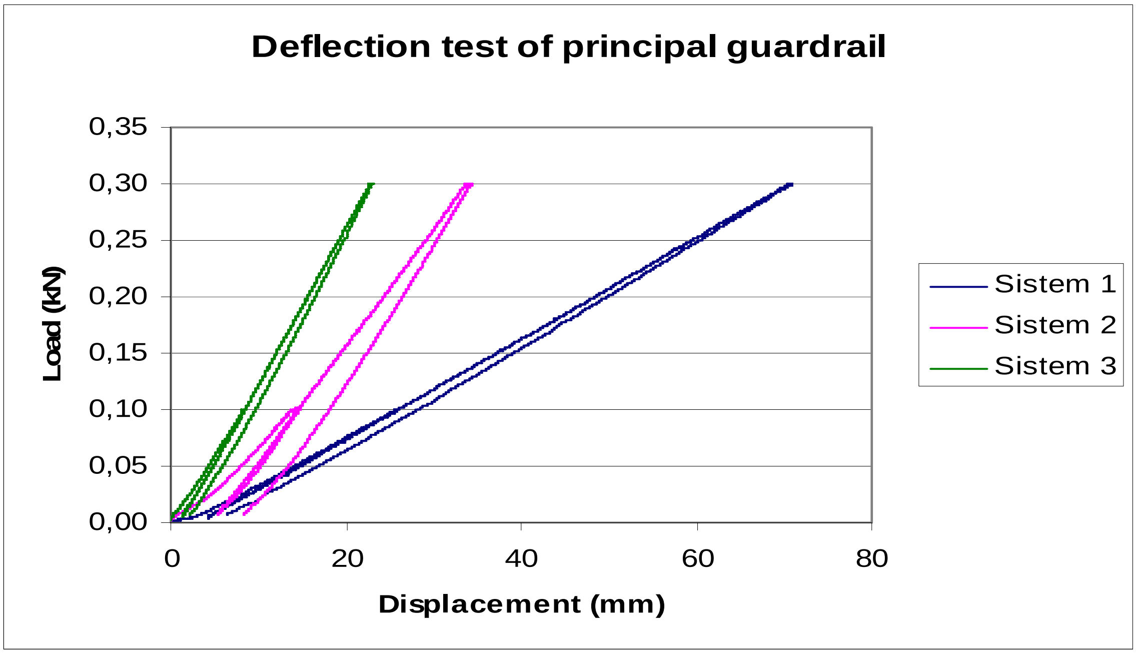


Figure 5. Results of the deflection test on the central point of principal the guardrail.

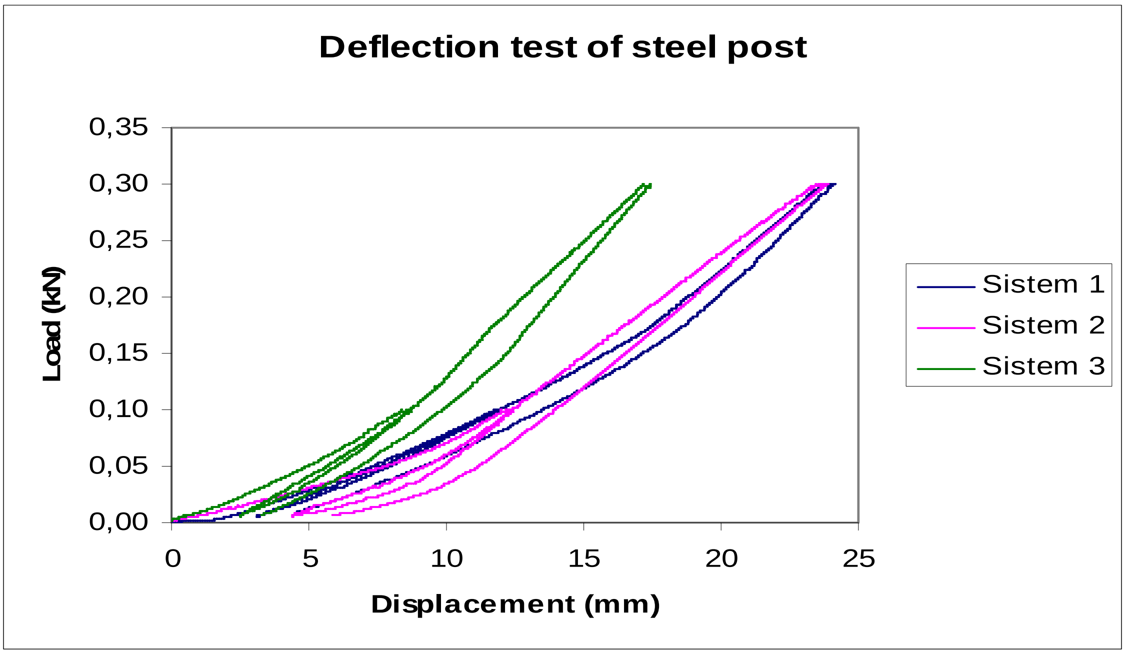


Figure 6. Results of the deflection test on the point at the upper part of the post.

The results of the strength test are show non figures 7 and 8, when the load is applied on the central point of the principal guardrail and on the cantilevered edge of the post, respectively.

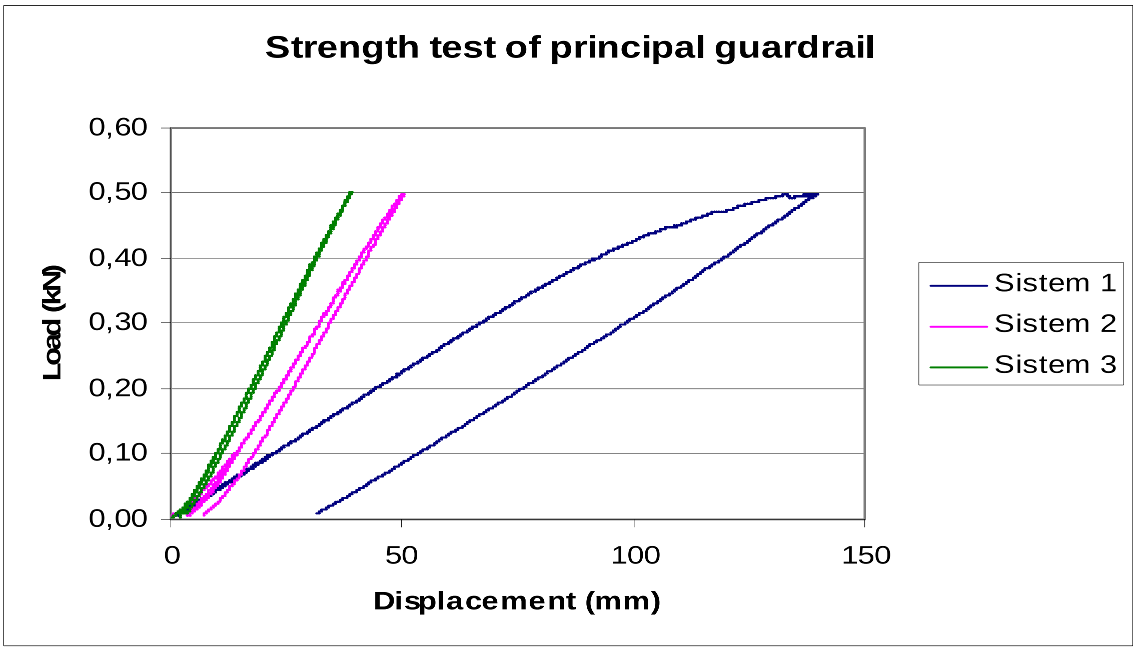


Figure 7. Results of the strength test at the central point of the principal guardrail.

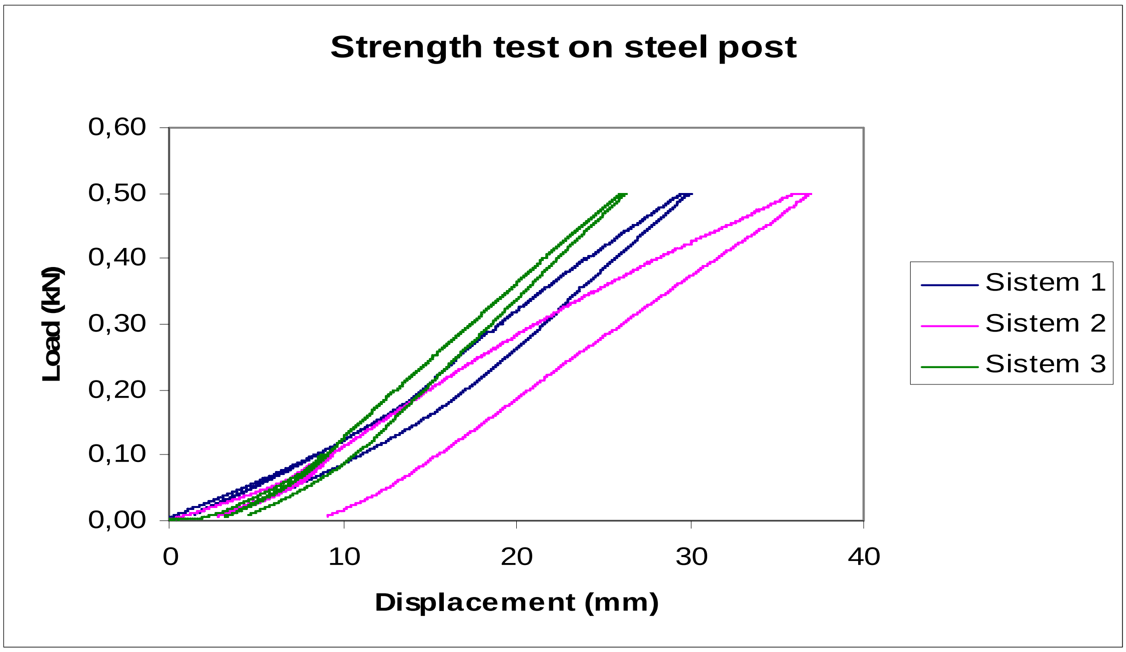


Figure 8. Results of the strength test on the upper point of the post.

Figure 9 shows the results of the deflection test and strength test performed on the toeboard.

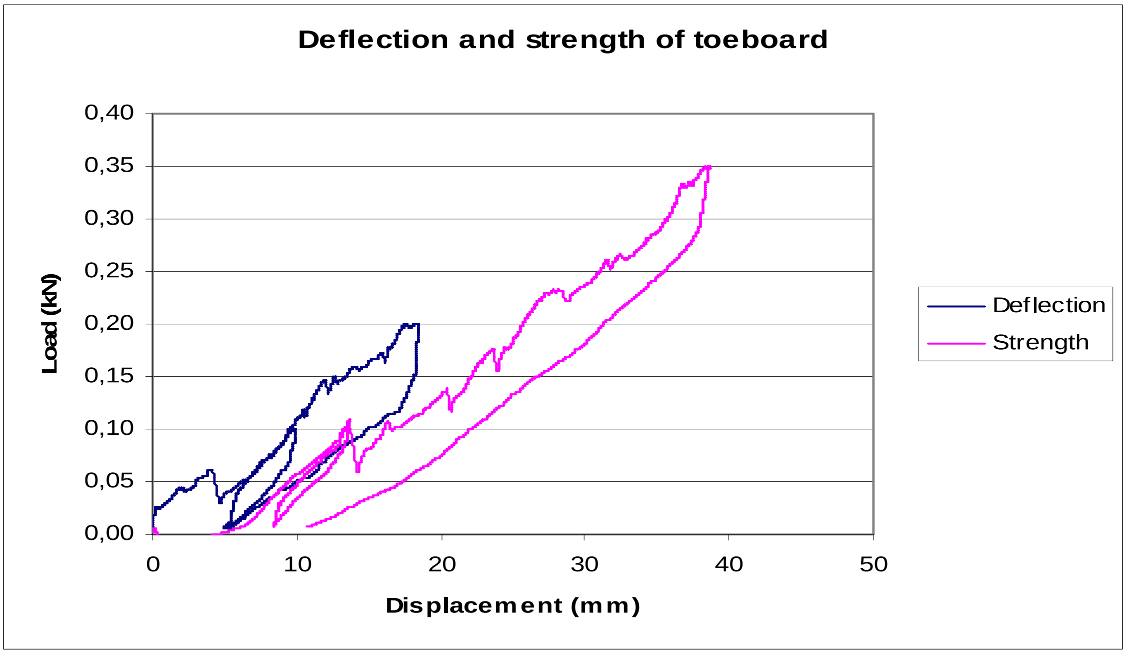


Figure 9. Results of the deflection test and strength test on the centre point of the toeboard.

From the systems analyzed, only system 1 has not successfully undergone the accidental loading test.

ANALYSIS AND RESULTS DISCUSSIONS

General results

The results indicated in table 2 show that system 3 is the only one capable of meeting the requirements stated by the UNE-EN 13374 standard for its experimental evaluation. System1, commonly used in construction works, does neither meet the deflection nor the strength requirements. System 2, used exceptionally in construction works does not comply with the strength test.

Deflection requisite

As can be seen in figure 5, the performance of the three systems is practically elastic and linear. System 3 is more rigid than 2 and in turn, the later is more rigid than system 1.

System 1 does not meet the requirement of deflection. When a 0.30 kN load is applied at the central point of the principal guardrail (figure 10), a movement greater than the limit established by the standard is obtained: 66.67 mm as opposed to 55 mm (table 2).

The movement of the post when the load is applied on the guardrail can be seen in figure 6, where for a 0.15 kN load, a movement of approximately 11.79 is obtained. Therefore, the guardrail suffers a deflection of 66.77 – 11.79 = 54.98 mm, practically 55 mm. This means that even when the post is infinitively rigid (impossible supposition) the guardrail by itself experiences a movement equal to the maximum admitted for the system, and hence the whole system is not valid.

Figure 10. Deflection test with load applied at the centre of the principal guardrail of system 1.

At the same time, the post suffers a movement of 20.98 mm (table 2) when the load is applied totally on it. This implies that with a guardrail rigid enough, it could pass successfully the deflection test. More precisely, in order to meet the requirements of this test, the guardrail could displace 55 – 10.49 = 44.51 mm.

The toeboard, with a movement of 13.43 mm, does meet the deflection requirement (table 2).

As the rigidity of the guardrail increases, system 2 is capable of meeting the deflection requirement. As can be seen on table 2, the system deflection when the load is applied at the centre of the principal guardrail is lower than the limit established by the standard (28.87 mm as opposed to a 55 mm). The same occurs in system 3, which maximum system deflection (21.66 mm) is even lower than that of system 2.

Post deflection of system 2 maintains similar values to those of system 1.

Increasing the rigidity of the guardrail section and post has produced significantly smaller movements to those of system 3.

Table 3 shows the system movement in the cases analyzed when a load of 0.30 kN is applied at the centre of the principal guardrail, separating the movement of the post and that of the guardrail.

Table 3. Displacement results of the three systems tested.

	SYSTEM 1	SYSTEM 2	SYSTEM 3
POST	○ 40 · 1,5 10,49 mm	□ 35 · 1,5 9,74 mm	○ 40 · 2,0 7,49 mm
GUARDRAIL	○ 25 · 1,5 56,18 mm	○ 40 · 1,5 19,13 mm	○ 40 · 2,0 14,17 mm
SYSTEM	66,67 mm	28,87 mm	21,66 mm

As can be observed, the post does not play a determinant role for the deflection requirement, and the three previous solutions show very similar deflection values for the post.

However, difference in the guardrail deflection in important. The change in tube dimension, from 40·1.5 to 40·2 implies a significant decrease in the guardrail deflection. Also, the 25·1.5, guardrail, n itself, has a greater deflection to the one established and allowed by the standard.

Graphs of figure 6 show an abnormal initial behaviour, as a consequence of the strain caused by the plastic pipe when the load is applied. This leads to non linear graphs and to rigidity when subject to loads. Once half of the test load has been applied, the behaviour is linear. Unloading is produced in an elastic way, following in a very approximate way, the curve corresponding to the load. On each of the posts the movement obtained is lower than the one allowed by the standard.

Strength requirement

Figure 7 shows the diagram force-displacement for a load applied at the centre point of the principal guardrail.

The rigidities of the three systems are highlighted once again. In system 1, the diagram is linear until about 0.40 kN load is applied. From that moment on, the system looses its rigidity gradually, as a consequence of the plastic process being produced in the system. When the maximum load is reached, and unloading starts, residual deflection is approximately 30 mm (30.07 mm). In this case, the system meets the standard for maximum load test but does not meet the other two requirements of the standard: residual deflection is 10% higher than the maximum instantaneous deflection one and the ultimate strength (0,57 kN) is not higher than 1.2 times the maximum test load, 0.60 kN, (table 2).

The performance of systems 2 and 3 is not linear, and practically no remaining strains can be observed. The three points indicated by the standard to be met regarding strength requirements are positively exceeded (table 2).

In the Force-displacement graph corresponding to the post of system 1 (figure 8), an abnormal performance is observed as the load increases. It produces a increase of the system rigidity, motivated by the deformations between the plastic pipe embedded in the beam and the metal post. When these deformations stop (approximately for 0.20 kN) the behaviour correspond to the beam rigidity. The maximum test load is reached and the unloading process is similar to that of the loading one. This implies that the deformations produced in the plastic pipes recover and hence, the post behaviour is elastic. The post satisfactorily passes the strength test.

When the load is applied on the post of system 2, from approximately 0.32 kN (figure 8) linearity fails, although the post is capable of resisting the maximum load of the test without fracturing and the ultimate load is higher to the specified value. At the same time, the remaining strain exceeds in 10 % to the instantaneous one, and therefore, the system should be considered as not valid (table 2).

Regarding the post of system 3, it is observed that once again the behaviour is elastic and the requirements of the standard are clearly surpassed (figure 11).

In figure 9 the big movement produced in the toeboard when the load is 0.10 kN can be observed. Later, it is unloaded to obtain the reference deflection. The force-displacement curve, both for deflection and for strength, shows the typical appearance of a saw-tooth, as a consequence of the displacements produced in the telescopic system of the toeboard. The maximum test load is reached, and the unloading is approximately linear. In this case, the deflection and strength test are successfully passed (table 2 and figure 9).

Figure 11. Strength test, applying the load on the post of system 3.

Comparison between analytical and experimental results

Table 4 shows the displacement values obtained analytically and experimentally of the three systems for the deflection test.

Table 4. Comparison between the analytical and experimental results for the deflection test.

		ANALYTICAL (mm)	EXPERIMENTAL (mm)
S 1	POST ○ 40 · 1,5	7,10	10,49
	SYSTEM	**60,70**	**66,67**
S 2	POST □ 35 · 1,5	6,32	9,74
	SYSTEM	18,54	28,87
S 3	POST ○ 40 · 2	5,51	7,49
	SYSTEM	15,03	21,66

As can be seen, for system 1, both analytically and experimentally the same results are obtained: the displacement requirement is not met. Systems 2 and 3 do meet the displacement requirement in the two assessment types.

The movements obtained in the experimental evaluation are greater than those analytically calculated for every case. The reason for it is that the result analytically calculated has been obtained using as a calculation model for the post a bracket post (figures 2 and 3). However, as can be seen in figures 6 and 8, the behaviour of the post does not correspond to the one of the built in model. Indeed, important movements can be observed as a consequence of the deformations from the plastic pipe in which the post is embedded. Hence, greater experimental movements are obtained than those considered analytically. It would be necessary, for the analytical assessment, to incorporate a model which considers the interaction post- PVC pipe.

Table 2 shows a summary of the results of calculation for USL and the strength test for the three systems. In the column corresponding to the analytical results, the values obtained for the stressing moment (M_{Sd}) and the moment capable of resisting the section (M_{Rd}) are included. The ULS checking needs that $M_{Rd} \geq M_{Sd}$. In the column with the experimental results, values of the test load (F_{H1}), ultimate strength (R_u) and residual deflection (δ_{res}) are indicated. The figures highlighted in bold correspond to situations in which the corresponding requirements are not met.

For System 1, the same results are obtained. The post meets the ULS, although barely so (0.48 kN·m as opposed to 0.45 kN·m), but the guardrail does not meet the flexural test (0.18 kN·m as opposed to 0.27 kN·m).

In the guardrail case, the condition established in the analytical calculation (stressing moment smaller than the moment the section supports) could be proved experimentally by checking that it is able to support the same test load. Experimentally, this condition is successfully met, whereas the other two conditions – residual deflection and ultimate strength—are not met and therefore the test is not satisfactorily passed.

In system, it can be proved that for the guardrail the same conclusions are obtained for the calculation of ULS and for the strength test.

Differences appear when comparing the results of the post. The post meets the ULS calculation and, however, when it is tested, it does not meet the strength test requirements because, although it supports the maximum test load and its maximum strength is 1.2 times higher than the test load, the residual deflection exceeds in a 10% the maximum instantaneous deflection.

The results difference is produced when the requirements stated by the standard for the experimental analysis are higher than the ones stated for the analytical calculation, as in the later only one of the conditions established in the experimental analysis is considered: supporting the maximum test load. This is what is done in analytical calculation, checking that the momentum the element section resists is higher than the momentum produced by the test load. However, in analytical calculation, the other two conditions required experimentally are not present: ultimate strength and residual deflection, and it is precisely this last condition of the residual deflection the one this post has not met.

In system 3, the same results are obtained by calculating the USL and the strength test.

CONCLUSIONS

1. A high percentage of the TEPS manufactured using a steel tube and commonly used in construction works in Spain comply with the UNE-EN 13374 standard as has been proved when analytically and experimentally assessed.
2. The 35 · 1.5 squared tube section is not capable of meeting the requirements of the strength test stated in UNE-EN 13374 standard.
3. Experimental assessment established by UNE-EN 13374 standard is more demanding than the analytical one, as it indicates two different verifications (ultimate strength and residual deflection) in the strength test which are not established for the analytical analysis. Due to this reason, the post indicated in the previous point does not meet the strength standard.
4. The system comprised by the 40 · 2 steel tube and the guardrail is capable of successfully meeting the requirements of the UNE-EN 13374 standard, both analytically and experimentally.
5. Combining the results of tables 4 and 5, systems made by guardrail and 40 · 1.5 tube section posts would also be able to meet the requirements of the standard, analytically and experimentally.
6. In order to carry out the deflection test analytically, it is necessary to incorporate the movement produced between the metal post and the PVC pipe to the model.

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