ACCELERATION AND DEFLECTION ANALYSIS FOR CLASS C EDGE PROTECTION SYSTEMS (EN 13374) IN CONSTRUCTION WORKS

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ABSTRACT

The requirements for class C edge protection systems in construction works (according to EN 13374 code) are studied in this paper. Maximum acceleration suffered by a falling body and maximum deflection of the protection system were analyzed through some finite element models and real size experiments. The aim of this work is to determine which value for deflection system entails an acceleration that is safe for the human body. This value is compared with the requirements given by current version of EN 13374 and an additional series of experiment were done to determine the acceleration linked to minimum deflection required by code. According to obtained results, a modification of this value is recommended. Additionally, a simple design formula for a falling protection system is proposed as a quick tool for the initial steps of design.

KEYWORDS: EN 13374, Edge protection system, Construction works, Safety nets

1.- INTRODUCTION

The current version of code EN 13374 [1] that was approved in 2004, contains general requirements for edge protection systems in order avoid accidents of construction workers due to height falls. The protective system usually consists of two parts: a rigid frame (typically metallic) and a net that is held by the frame (figure 1).

Figure 1: Safety protection net system

The code classifies the safety protection systems according to the working plane slope and the fall height, as it is detailed in figure 2. There are also requirements about the kinetic energy that the protection system should absorb and the corresponding minimum deflection of the system. In particular, for class C, the system should absorb a kinetic energy of 2200 Joules with a minimum deflection 200 mm for a 75 kg body falling by a working surface with a slope of 60° and 5 m high.

Figure 2: (a) Working plane slope and fall height definition, (b) Range of these parameters for the protection system considered in EN 13374

Minimum deflection of the system required by the code under the conditions just exposed was not reliable for the authors, since previous studies in the literature obtain much higher deflection values under similar conditions than those in the code. In 1985 Bellmunt [2] did some experiments using horizontal nets and the deflection measured was between 850 and 1430 mm for a 7 m high fall. From code EN 1263-2 [3] we can infer that this deflection should be up to 2500 mm for a 6 m fall. Even though the fall height in these studies is higher than the one addressed here, the difference with the deflection given by the code is high enough to encourage a detailed analysis of this parameter.

In the study of general fall protection systems, one key parameter is the maximum acceleration that human being can support without suffering serious damage. Unfortunately, the damage threshold has not been clearly stated. Paureau [4, 5] did some theoretical studies related with this acceleration and use a limit value of 17 g. Gonzalez and Ríos [6] use a value of 9 g for their studies, while for Voshell [7] the

maximum value that human being can support without losing of consciousness is 10 g; nevertheless, the conditions in this last case were somehow particular because the man was seated and the acceleration was continuously applied during some seconds. For falls with body harness, Sulowski [8] uses values around 7 g, or even lower. However, the fall with a body harness is harder than the fall in a net, because the area that receives the impact in the first case is smaller than in the second case. According to all consulted literature we consider that a maximum acceleration value of around 10-12 g is an adequate damage threshold, and consequently will be considered here for our calculations.

In order to evaluate the deflection in the protection system, a normalized experiment was done. We followed the procedure stated in code EN 13374 with a conventional thread net. As expected, the deflection measured was much higher than that required by the code. Therefore, in order to adjust the different variables of the experiment to the code requirements, a FEM model was implemented. With it we determine the stiffness needed for the system to provide the minimum deflection, and therefore the material needed for the net and the cross section for the supports. Then, the acceleration linked to this value of deflection was determined and compared with harming level previously stated (12 g). Finally, to asses the results obtained through FEM analysis, a new experiment was done on a real sample, using the structural characteristics given by FEM model for a 200 mm deflection.

2.- NORMALIZED EXPERIMENT WITH A CONVENTIONAL NET

Conditions for a normalized experiment for class C protection systems are detailed in codes EN 13374 and EN 1263-1 [9]. Working surface should be flat and sloped 60°.

The human body is simulated with a cylinder body of 75 kg, 300 mm of diameter and 1000 mm of length. A layer of rubber should externally cover this ballast with 25 mm thickness. During the experiments, previous to the free fall, the body centre of gravity should roll a distance of 5 m on the slope (figure 2).

With these conditions, four different experiments were done with a conventional net held by steel support frames with a span between supports of 4 meters. Two of these experiments were done by throwing the cylinder in the middle of two supports (net midspan), while for the other two the cylinder was thrown in front of the central support (in support plane). The used net was 8x2 m, with squared 100 mm side holes. The net is made using textile cord with 16 threads, 3500 dtex each one and with a strength higher than 3 kN. The slope of the net was 50° with respect to the vertical and the slope of the working surface was 60° with respect to the horizontal, within the range of values stated in code for class C. In figure 3(a) a general view of the experiment is shown, with the cylinder hanging in the upper part of the ramp, ready to start the experiment. Figure 3(b) shows slopes of both working surface and net.

Figure 3: (a) General view of the experiment (b) Slopes of working surface and net

The two parameters most relevant to our work are the acceleration suffered by cylinder and deflection of the protection system. To measure the acceleration, an ICP triaxial accelerometer was placed in the axis of the cylinder (figure 4). Acceleration measurement and frequency ranges of the accelerometer were 500 g and 900 Hz, respectively. A high-speed camera (AOS XPri), working at 500 frames per second, was used to measure the maximum deflection of the system (figure 5).

Figure 4: Accelerometer in the centre of cylinder

Figure 5: High speed camera

The results given by accelerometer in the first trial are shown in figure 6, as an example of the rest of them, since the shape of the curve is similar in all of them. Maximum value obtained in this experiment is around 11 g. To measure the deflection of the

system, the images obtained from the high speed camera were used. The image corresponding to maximum deflection has been superimposed (figure 7) to the image corresponding to the moment in which the cylinder starts the contact with the net. Therefore, the maximum deflection can be directly measured on this compound image by joining the centre of two circles in the figure 7 (red line) and making a proportional relation between pixels and a known real distance. In our case, our reference distance is the cylinder diameter providing a ratio of 0.46 px/mm. With this, we obtain a deflection around 850 mm for the first impact.

Figure 6: Acceleration obtained by accelerometer for the first impact in midspan

Figure 7: Measurement of maximum deflection of the protection system for the first impact

Curves and proceduree followed for the other three experiments were similar to those obtained here, so they have not been depicted here. In Table 1 we summarize the resulys for the four normalized experiments done with conventional net. There we can appreciate that the acceleration suffered by the cylinder increases as the deflection becomes smaller. This happens because smaller deflections mean shorter events and harder impacts and consequently higher accelerations. In all cases, maximum deflection is higher than 600 mm, being the maximum 850 mm. By comparing these values with the threshold value stated in the code (200 mm), it is clear that this value is cleary underestimated. Notice also that, for such long deflections the acceleration obtained for the maximum deflection has been 11 g, in the limit of the damage threshold for human beings. Thus, a safe system must consider deflections even larger than 800 mm, which is 4 times higher than the value stated in the code.

Test	Maximum deflection (mm)	Maximum acceleration (g)
Net midspan 1	850	11
Net midspan 2	800	12
In support plane 1	750	13
In support plane 2	650	16

Table 1: Maximum deflection and maximum acceleration obtained in all experiments done with conventional net.

3.- SIMULATIONS THROUGH A FINITE ELEMENT MODEL

Next step in our work was to find a protective system that provides a deflection of 200 mm in a normalized experiment. Then maximum acceleration linked with this deflection can be calculated. To do that, the first step was to implement a finite element model and

find the structural and strength characteristics of the net and the supporting frame that provides such deflection.

The finite element model was implemented with ANSYS code [10]. At first we used conventional materials in order to adjust the behaviour of the model to the experiments already done: for the net a “Link 10” element was used, with linear elastic behaviour. Equivalent axial stiffness and damping ratio for this material (610 N and 0.34, respectively) were taken from Segovia et al [11] for safety nets V type [3]. The stiffness is a compromise value considering the knots in the thread at the initial state and after one impact when the knots are tighten and the the length of the thread increases. The equivalent axial stiffness also takes this effect into account.

Two different elements were used to simulate the cylinder: “Shell 181” for the metallic interior part and “Solid 45” for the rubber cover. The metallic supports were modelled as tubular metallic bars with external diameter of 48 mm and thickness of 3 mm. The element used for the supports was “Beam 188” with an elastic modulus of 210 GPa and a yield strength of 275 MPa. Also, elements “Conta” and “Targe” were used to simulate the contact between the cylinder and the net.

The model was calibrated with the experimental results given in the previous section. From that, stiffness of net and supports was increased until the maximum deflection obtained was 200 mm (figure 8). To obtain that deflection it was necessary an equivalent axial stiffness of 9000 N for the net and triplicate the original section of the supports.

With this protective system configuration, the maximum acceleration obtained was higher than 30 g, 3 times higher than the maximum that human being can support. Then it is proved that taking the protective system to the limit value given by code can be potentially unsafe.

179

180 Figure 8: Result of the finite model adjustment to have 200 mm of maximum deflection

181

182 In order to confirm the values obtained through finite element model, additional
183 experiments were done using the values of stiffness for the net and supports that were
184 obtained in this section.

185

186 **4.- NORMALIZED EXPERIMENT WITH STEEL WIRE MESH NET**

187 The requirements obtained for the stiffness of the net are fulfilled by using a steel wire
188 mesh net in the experiments. Also, the steel frame was reinforced by triplicating the
189 number of tubes in each support.. Figure 9 shows the preparation of the steel wire mesh
190 in the reinforced frame.

191

Figure 9: Preparation of the experiment with steel wire mesh net and reinforced frame

With this protection system two experiments were done. In both of them the cylinder was thrown in front of one central support in order to produce smaller deflections. Measurements were taken following the same instruments and procedures than in the previous experiments. The results are shown in table 2.

Test	Maximum deflection (mm)	Maximum acceleration (g)
In support plane 1	235	30
In support plane 2	185	40

Table 2: Maximum deflection and maximum acceleration obtained in all experiments

done with steel wire mesh net.

Mean value of maximum deflection obtained in these two experiments was around 200 mm, which coincides with the value obtained through finite element models, and the

minimum value recommended by code. For this deflection, the corresponding acceleration is between 30 and 40 g, as we also obtained in our simulations.

Results here presented are a strong proof that considering a deflection of 200 mm, which falls inside the values recommended by the code, would imply very strong accelerations (30g) which may be really dangerous for the workers. Consequently we propose a value for minimum deflection of the system around 800 mm, in order to have a safe acceleration of 10-12 g.

5.- QUICK DESIGN FORMULA

Results obtained through the numerical models are the velocity, displacement and acceleration curves of the cylinder from the moment in which the cylinder first touches the net until the moment in which its velocity is zero. For all the simulations done, the shape of these curves was similar. One example of these curves is shown in figure 10(a). Based on these curves, it is possible to make a simplified analysis of the falling and trapped body by obtaining an analytical expression for the three kinematic variables and then, a relation between them thus obtaining a simple formula connecting the maximum deflection of the net, the fall height and the impact factor, defined as the ratio between maximum acceleration and g.

Notice that maximum deceleration is very closely located at one third of the total time of the event and the two parts in which this maximum divides the acceleration curve can be modelled as straight lines (figure 10(b)).

Figure 10: (a) Example of variation of acceleration, velocity and displacement of cylinder in time, obtained through numerical simulations, (b) mathematical modelling of these curves to be used in a simplified kinematic analysis

The symbols used in this part are:

Δ : Time from the starting to the moment of minimum acceleration

$a_1(t)$: Acceleration in the first part of the event (from the starting until Δ time)

$v_1(t)$: Velocity in the first part of the event (from the starting until Δ time)

$s_1(t)$: Displacement in the first part of the event (from the starting until Δ time)

$a_2(t)$: Acceleration in the second part of the event (from Δ time until 3Δ time)

$v_2(t)$: Velocity in the second part of the event (from Δ time until 3Δ time)

$s_2(t)$: Displacement in the second part of the event (from Δ time until 3Δ time)

h : Initial fall height

v_0 : Initial velocity

g : Acceleration of gravity

f : Maximum displacement of the cylinder from initial contact to null velocity

245 a : Maximum deceleration of the cylinder from initial contact to null velocity

246 A, B : Auxiliary parameters

247 γ : Impact factor

248

249 Based on figure 10(b) we can obtain the corresponding acceleration in parts 1 and 2 of
250 the event, and, by integration, determine the corresponding velocities and
251 displacements. For simplicity we take the first instant when the acceleration of the
252 cylinder is zero, just after the first contact with the net. Then, for the first part of the
253 event, acceleration, velocity and displacement are:

254
$$a_1(t) = -\frac{a}{\Delta}t \quad (1)$$

255
$$v_1(t) = -\frac{a}{\Delta}\frac{t^2}{2} + v_0 \quad (2)$$

256
$$s_1(t) = v_0t - \frac{a}{6\Delta}t^3 \quad (3)$$

257 And, for second part of the event:

258
$$a_2(t) = -a + \frac{t-\Delta}{2\Delta}a \quad (4)$$

259
$$v_2(t) = \frac{a}{2\Delta}\frac{t^2}{2} - \frac{3a}{2}t + A \quad (5)$$

260
$$s_2(t) = At - \frac{3a}{4}t^2 + \frac{a}{12\Delta}t^3 + B \quad (6)$$

261 Now, we impose boundary conditions for parts 1 and 2, since at the instant Δ both
262 velocities and displacements should be the same. Therefore in equations 2, 3, 5 y 6, we
263 can determine the value of auxiliary parameters A and B :

264
$$v_2(\Delta) = v_1(\Delta) \quad (7)$$

265
$$A = v_0 + \frac{3}{4}a\Delta \quad (8)$$

$$s_2(\Delta) = s_1(\Delta) \quad (9)$$

$$B = -\frac{a\Delta^2}{4} \quad (10)$$

Also, at time 3Δ velocity should be equal to zero, so we can determine Δ in function of v_0 and a :

$$v_2(3\Delta) = 0 \quad (11)$$

$$\Delta = \frac{2v_0}{3a} \quad (12)$$

Then, knowing the value of v_0 :

$$v_0 = \sqrt{2gh} \quad (13)$$

We can write the maximum displacement in function of h , g and a , using equation (13):

$$f = s_2(3\Delta) = \frac{8}{9} \frac{v_0^2}{a} = \frac{8}{9} \frac{2gh}{a} = \frac{16}{9} \frac{hg}{a} \quad (14)$$

The impact factor is defined as the ratio between maximum acceleration and g . From equation (14) we obtain :

$$\gamma = \frac{a}{g} = \frac{16}{9} \frac{h}{f} = 1.77 \frac{h}{f} \quad (15)$$

This last expression (15) is a very simple equation that relates the impact factor (γ) with fall height (h) and maximum displacement of the cylinder (f), i. e. maximum deflection of the system. This expression can be used as a quick tool in the designing of this type of protection systems.

283

284 6.- CONCLUSIONS

285 The analysis of the minimum required deflection in EN 13374 code for class C is done
286 in this work. Some normalized experiments according to this code were accomplished
287 to determine the deflection obtained using a conventional protection system, as it was

defined in section 2. Acceleration and deflection were measured using an accelerometer and a high speed camera. Since the maximum deflection is related to the maximum acceleration, this last value was used to determine whether the obtained deflection is admissible, taken a limit value of 10-12 g as maximum acceleration that human being could support. Results show such accelerations are accomplished with deflections around 850 mm. Therefore, smaller values for deflection, as the one required by EN 13374 code (200 mm), may not be safe for human being.

To deepen in this subject, we established as an additional goal the determination of the maximum acceleration linked to a 200 mm deflection. Results from some finite element models and new experiments with a strengthened protection system give accelerations higher than 30 g, which is 3 times higher than the maximum allowed by human body. Based on our models and experiments, we propose a modification of the EN 13374 code, in which a value of 800-900 mm would be required as minimum deflection for class C protection systems to be safe for construction workers.

Additionally, a simplified formula was obtained that shows an impact factor being proportional to the rate between fall height and the maximum displacement of the protection system. Although simple, this formula may be useful as a quick approximation in the design of protective systems.

ACKNOWLEDGMENTS

B. Ferrer acknowledges the support of the University of Alicante through the project GRE10-09 and the support of the Generalitat Valenciana through the project GV/2013/009. We also acknowledge the comments and revisions of D. Mas.

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In support plane 2	185	40

Table 2: Maximum deflection and maximum acceleration obtained in all experiments
done with steel wire mesh net.

Figure 1
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Figure 2a
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Figure 2b
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Figure 3a
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Figure 4
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Figure 10a
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