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Experimental testing of rockfall barriers designed for the low range of impact energy

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Experimental testing of rockfall barriers designed for the low range of impact energy

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Abstract

Most of the recent research on rockfall and the development of protective systems, such as flexible rock fall barriers, have been focused on medium to high levels of impacting energy. However, in many regions of the world, the rockfall hazard involves low levels of energy. This is particularly the case in New South Wales, Australia, because of the nature of the geological environments. The state Road and Traffic Authority (RTA) has designed various types of rockfall barriers, including some of low capacity, i.e. 35 kJ. The latter were tested indoors using a pendulum equipped with an automatic block release mechanism triggered by an optical beam. Another three systems were also tested, including two products designed by rockfall specialised companies and one modification of the initial

design of the RTA. The research focused on the influence of the system's stiffness on the transmission of load to the other components of the barrier such as posts and cables. Not surprisingly, the more compliant the system, the less loaded are the cables and posts. It was also found that removing the intermediate cables and placing the mesh downslope could reduce the stiffness of the system designed by the RTA. Finally, the paper concludes with some multi scale considerations on the capacity of a barrier to absorb energy based on experimental evidence.

Keywords: Rockfall Barrier, Pendulum, Stiffness, Mesh, Multiscale, Energy

1. Introduction

Most of the recent research on rockfall and the development of protective systems, such as flexible rock fall barriers, have been focused on medium to high levels of impacting energy, typically in excess of several hundreds of kilojoules (Duffy, 1992a, Peila et al., 1998, Peila et al., 2007, Peila, 2011, Trad et al., 2011). Bigger systems have progressively been developed: the ETAG027 guidelines include a class for impact energy larger than 4500 kJ and capacities of 5000 kJ have been achieved (Trad et al., 2011). Such high levels of energy are typically relevant in exposed environments such as coastal roads like Chapman's Peak drive in South Africa (Volkwein et al, 2005) or in mountainous areas like the Alps or the Rocky Mountains.

1 However, in many other regions of the world, much lower values of impacting
2 energy have to be accounted for. Muraishi et al. (2005) surveyed 607 rockfall
3 events in Japan, of which 68% involved levels of energy lower than 100 kJ.
4 Similarly, there are regions of Australia where a rockfall hazard does exist but
5 involves low levels of energy. This is due to the nature of the geological
6 environments in New South Wales (Fityus et al., 2012), which are inherently
7 different from the mountainous areas of Europe or Northern America. To
8 mitigate the rockfall hazard, the Road and Traffic Authority of New South Wales
9 (RTA) has designed rockfall barriers of 4, 35 and 350 kJ of capacity. Note that a
10 large part of the infrastructure network only requires the lowest two levels of
11 protection.
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30 Different types of rockfall barriers have been studied in the literature and those
31 whose capacity is less than or equal to 200 kJ are often classed as low energy
32 barriers (e.g. Duffy and Hoon 1996, Duffy 1992b, Hearn et al. 1995). Herein, the
33 range 100-200kJ is considered to be of medium energy and capacities below 100
34 kJ are referred to as low energy. This corresponds to the energy levels not
35 covered by the lower class of ETAG027 (Peila and Ronco, 2009). For such levels
36 of energy, rigid barriers can be used as an alternative to flexible systems
37 (Descoeurdes, 1997; Grassl et al. 2003), provided the structural elements can
38 withstand the impact loads which are much higher than for flexible systems.
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54 Low energy barriers tested in the past include those reported by Hearn et al.
55 (1995), Muraishi et al. (2005), Kane and Duffy (1993) and Chan et al., (1986).
56 Most of these studies focused on the performance of the systems and the
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1 maintenance aspects. Chan et al (1986) designed a 100 kJ barrier but did not
2 actually test it in the field. Muraishi et al. (2005) emphasised the importance of
3 ground conditions and the foundation type, which is particularly relevant if high
4 loads are transferred to the foundations.
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11 The significance of load transfer within the barrier is generally recognised as a
12 key point in a successful design. Peila et al. (1998) and Peila and Oggeri (2006)
13 investigated the load transfer in the structural elements and energy dissipators.
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15 Duffy (1992b) proposed a flow chart explaining the mechanisms of energy
16 dissipation in the barrier, but did not appear to apply it to many case studies.
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27 This study investigates the impact of barrier stiffness on the transmission of
28 load to the structural elements (cables and posts). Four low energy barriers (35
29 kJ) have been tested using a pendulum and a 665 kg block. While using a
30 pendulum to impact barriers is not new (Peila, 2011, Yoshida, 1999), as far as
31 we are aware, this is the first time it is employed indoors together with an
32 automatic release system. The first system to be tested was designed by the New
33 South Wales Roads and Traffic Authority (RTA) and is considered semi-rigid.
34
35 Indeed, it includes rigid posts, a chainlink mesh placed uphill and horizontal
36 cables placed across the mesh. Note that Hearn et al. (1995) also proposed a low
37 energy barrier design including several intermediate cables across the mesh,
38 which generates a high level of stiffness. However, this high stiffness was
39 compensated for by the use of flexible posts.
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1 The RTA design was later modified with the objective of diminishing the barrier
2 stiffness, thus modifying the mechanism of load transmission. The key idea
3 behind the modification was for the barrier to catch the block while minimizing
4 the damage to the system or confining it to the components that can be easily
5 replaced (e.g. the mesh). Finally, two new flexible products of varying stiffness,
6 from Geobruigg and Maccaferri, were tested to complete the study.
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17 Although the stiffness of a rock fall barrier is widely recognised as a key element
18 in its performance, it is seldom quantified. In this study, the values of stiffness
19 have been determined for four rockfall barriers, which is useful for models
20 based on this parameter (e.g. Dhakal et al. 2011; Spadari et al., 2011). The
21 novelty of this paper lies in the determination of the complete load-deflection
22 curves, using photographs from high-speed cameras, which allows the system
23 stiffness to be quantified. Also, loads were measured at different locations in the
24 barriers to highlight the impact of the stiffness on the load dissipation, from the
25 mesh through to the foundations. Finally, some observations are made about the
26 multi-scale capacity to absorb energy based on the experimental results.
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44 **2. Experimental facilities**

45 **2.1) Testing setup**

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51 For the series of tests, a pendulum was designed and built at the Newcastle
52 Institute for Energy and Resources (NIER) at The University of Newcastle. An
53 overhead crane was used to lift the block and to fix the pivot point, as shown in
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Figure 1. As the crane is not designed to withstand transverse forces or to suddenly release a load, a set of five chains was added to the system. These chains, pre-tensioned before each test, were designed to take the lateral forces resulting from the acceleration of the block along its circular path, thus avoiding any rebound of the crane post-release.

The concrete density and shape of the impacting block was built according to the ETAG027 guidelines (EOTA, 2008). The block was lifted higher than the pivot point in order to reach about 35 kJ of energy (mass of 665 kg, dropping height of 5.3 m). This required the use of a rigid arm, rather than a cable, to avoid slackness and shocks. Two pneumatic quick releases (QR) were used: the first one (QR1, capacity 10 kN) to drop the block from its highest position and the second (QR2, capacity 45kN) to release the block from the swinging arm at its lowest point. In the following, the “drop” refers to release by QR1 while the “release” refers to release by QR2. The second quick release has a higher capacity to withstand the force resulting from the centrifugal acceleration: the tension at the lowest point reaches 25 kN.

HERE FIGURE 1

The drop was triggered manually, but a more controlled and repeatable system was designed for the release using an optical beam that was placed about 500

mm before the barrier. When the block crossed the optical beam, a signal was sent to the QR to release the block (Figure 1). This simple system ensured that the block became free at its lowest point and travelled on a horizontal trajectory. The exact location of the beam was decided after determination of the QR's release time, which was measured under different static loads using high-speed cameras.

2.2) Materials and Barriers

Four systems were tested, the characteristics of which are summarised in Table 1. This includes two products by Maccaferri and Geobrugg, which are referred to as systems M and G, respectively. These barriers were designed as flexible solutions and are expected to have different stiffnesses due to their inherent differences in construction (see Table 1).

A semi-rigid barrier, designed by the Roads and Traffic Authority, was also tested. This is made of "off-the-shelf" components rather than specific products designed for rockfall, and will be referred to as OS1. This system was modified to create another off-the-shelf system, referred to as OS2. This modification consisted of removing the intermediate cables, placing the mesh downslope, using smaller posts (for economic reasons) and connecting the mesh to the end posts. The same notation was used to identify a system and its mesh, i.e. system G is made of mesh G. The same mesh was used for systems OS1 and OS2, and is referred to as mesh OS.

Table 1: Characteristics of the four barriers tested (OS1, OS2, G and M). All barriers have 5 m post spacing and are 2 m high. Mesh aperture is taken as the shortest dimension between two nodes across the elementary cell of the mesh. OD: outer diameter, T: thickness, B: base, H: height. All dimensions are in mm. VC+S: Vertical cable plus shackles. WAC: wrapped around the vertical cable.

	OS1	OS2	G	M
Post Section (PS)	Circular	Circular	I beam	Circular
PS Dimensions	OD165/T5	OD133/T4.5	B150/H160/T8	OD133/T4.5
Post stiffener	No	No	Yes	Yes
Diameter top/bottom cables	16	16	14	16
No. of cables across the mesh	3 (16 mm)	None	None	None
Mesh type	Ordinary Chainlink	Ordinary Chainlink	Chainlink with high tensile strength	Composite double twist
Mesh location	Upslope	Downslope	Downslope	Downslope
Mesh wire diameter	3.15	3.15	4	3
Mesh aperture	75	75	100	80
Strength of mesh component [MPa]	≈ 500	≈ 500	≈ 2000	≈ 500 (wire) 1770 (cable)
Connection Mesh/Cables	3 mm tie wires (≈ 200 mm spacing)	7 mm cable	Steel helix	7 mm cable
Connection Mesh/end posts	None	VC+S	VC+S	WAC + VC+S

As per the ETAG27 guidelines (EOTA, 2008), the barriers were built with three panels. The tests were conducted indoors, with little possibility to vary or study

the effect of the foundation type. The posts were securely anchored so that the bolts would not be pulled out from the concrete floor.

The mechanical properties of the wire constituting the different meshes, as well as the different mesh types, are shown in Figure 2. Mesh-G is a chainlink of high tensile strength having a diamond shape cell while Mesh-M is a double twist incorporating an undulating 7 mm cable (see Figure 2). Technical details about these products can be found from the websites of the companies. It can clearly be seen on the figure that the rockfall dedicated products both have a high potential for energy absorption: Mesh-G has a high strength but low failure strain while the wires of Mesh-M has a lower strength but a high failure strain. In contrast, the off-the-shelf mesh has both a limited strength and a low failure strain.

HERE FIGURE 2

2.3) Sensors and Data logging

The barrier deformation upon impact was captured using two high-speed cameras at 500 frames per second (Optronis, CR600), controlled by the Camcontrol software (Optronis). About 400 photographs were taken per impact. The image tracking software TEMA was used to infer the position of the block with time from the sequence of photographs.

The barrier was equipped with load cells on the top, bottom and intermediate (if any) cables and at the base of posts 3 and 4 (see Figures 1c, 3a and 3b). The load cells were connected to a high frequency data logger (USB Compact DAQ system from National Instrument 9234), which can record up to 2048 data/s. This ensured that the peak load was recorded, as it will be shown in section 3.

HERE FIGURE 3

2.4) Calculation of an equivalent static load

This study focuses on the system stiffness and its influence on the load distribution within the barrier. The stiffness was inferred from the load-deflection curves, which were plotted using high-speed photography. The deflection was obtained directly from the photographs using a reference length, while the equivalent static load was calculated as the product of the block mass and its deceleration. The latter quantity has to be inferred from the block's motion, using differentiation of its position to obtain its speed. This was achieved using the image tracking software TEMA. However, small oscillations in the block's position (due to image resolution and vibrations) were amplified by the differentiation step leading to oscillating velocities (see Figure 4). A further differentiation step would generate even larger oscillations and lead to noisy data. Consequently, the velocity plot was fitted with a monotonic curve (see the dashed line in Figure 4) which was used to define the block deceleration $a(t)$ at a time t with respect to the moment of impact as:

$$a(t) = (v_o - v(t)) / (t - t_o) \quad (1)$$

where v_o is the block's velocity at impact and t is the time elapsed since impact which occurs at $t_o = 0$.

HERE FIGURE 4

3. Results and Discussion

Figure 5a shows the block being caught by the barrier M after having been released from the rigid swinging arm. Some padding can be seen around the QR to avoid any damage upon impact. The controlled release system was found to function perfectly and the block was consistently released a few centimetres before impacting the barrier on a horizontal path. The systems G, M, OS1 and OS2 were impacted with energies of 30.4, 32.3, 32.3 and 33.4 kJ, respectively.

In all cases the block was stopped by the barriers, which experienced different levels of local damage. System G was the only one to not sustain any damage but only permanent deformation of the mesh (as shown in Figure 5c). The deformation pattern visible in Figure 5c for the Mesh-G is consistent with the results of numerical models (Spadari et al, 2011; Anderheggen et al., 2002), where a cross-shaped pattern of mesh distortion has been observed. Here, only one branch of the cross is visible since a real system is not perfectly symmetrical and the phenomenon of localization at the onset of yielding prevents the full cross from developing. This did not happen with the other chainlink barrier

(Mesh-OS) because of damage at the connections with the top and bottom cables (Figure 5b). Note that the cross-shaped deformation pattern is not evident for the double twist mesh. This is believed to be due to the shape of the elementary cell causing another mechanism of stress propagation within the mesh.

HERE FIGURE 5

The load-deflection curves for the four barriers are shown in Figure 6. Systems M and G are the most compliant, with a stiffness of 16 and 18 kN/m, respectively. This is not surprising as these barriers were designed as flexible solutions. However, the similar values of stiffness are somewhat surprising, considering the inherent differences in the types of mesh, the connections and the material properties (see Table 1 and Figure 2). In particular, the 7 mm woven cable (see Figure 2c), which was introduced in the Mesh-M in order to improve its performance, does not seem to increase the overall system stiffness, at least, not in the way this latter is calculated in this paper. Some local damage was observed post-impact, which is thought to have occurred at maximum deflection, when the undulating cables have straightened and turned into a stiff point. Unfortunately, this was not captured by the high-speed cameras.

As expected, the system OS1, which incorporates three intermediate cables across a mesh placed upslope (see Figure 1b), is the stiffest. For this barrier, the block has hit the cable at mid height and the stiffness (estimated from the initial linear part of the behaviour) was estimated to be 35 kN/m. This is due to the fact that the cables prevent optimal loading and deformation of the mesh. A key

consequence of this design is that a low portion of energy is actually absorbed by the mesh itself and high loads are transmitted to the posts and foundations.

Removing the intermediate cables and placing the mesh downhill with respect to the posts yield a more compliant system (stiffness estimated to be 25kN/m), although more compliance was expected. The repercussion of this lower stiffness is that the mesh absorbed a high amount of energy and sustained more damage. Being a chainlink of low tensile strength (about 500 MPa), the Mesh-OS unravelled at the end of the mesh strands creating large openings below and above the impacted zone. This damage, in turn, resulted in less loading of the structural elements.

Interestingly, apart for the mesh, the construction of the systems OS2 and M is quite similar (same posts, similar connection types, comparable top and bottom cable – see Table 1) but these two barriers exhibit very different stiffnesses. It seems logical to impute this difference to the type of mesh, even though more compliance would have been expected from a chainlink compared to a double twist. This result remains unexplained, but shows that the mesh itself plays a key role in the overall stiffness of the barrier, especially at low levels of energy.

HERE FIGURE 6

In the following, the system stiffness was correlated to the load induced within top and bottom cables and at the base of the posts. Figure 7 confirms that the

peak load have been successfully recorded, since the peak is clearly captured with a logging frequency of 2000 records per second,.

HERE FIGURE 7

Figure 8, which shows the forces within various structural elements (cables and bases of posts) as a function of the barrier stiffness, corroborates the qualitative conclusions presented previously. It is clear that the stiffer the system, the higher the forces transmitted to the cables and posts. The anchors of system OS1 are loaded 3.5 to 4 times more than for systems M, G and OS2. Note that removing the intermediate cables from OS1 suffices to drop the load on the anchors to much lower levels. High loads on the anchors have a significant repercussion on the design of the foundations as these have to withstand the load. In fact, some anchors did fail during trial testing and the base plates had to be modified to mitigate this issue (as it was not the focus of the paper).

Similarly, the stiffer the system, the higher the load recorded in the top cable. Loads of about 48 kN, 40 kN, 23 kN and 31 kN were recorded for systems OS1, OS2, G and M, respectively. Unfortunately, no value was recorded for the bottom cable of OS1 and post 3 of G, due to technical issues.

Adding intermediate cables in the barrier brings the risk of having these hit directly by falling boulders, which may then generate loads in excess of 100 kN

1 and significant bending of the posts (Figure 9). This effect was recognised by
2 Hearn et al. (1995), who employed flexible posts to compensate for the high
3 stiffness arising from horizontal cables placed across the mesh. Figure 8a shows
4 that using smaller posts for system OS2 is not an issue as lower loads were
5 transmitted to the structural elements. The load in the bottom cable is higher
6 than that in the top cable for systems M and OS2. Regarding the former, the
7 result is believed to be inherent to the system, while for the latter it is related to
8 the type of damage sustained by the mesh (unravelling at the connection with
9 the top and bottom cables under large tensile loads). This also applies to the top
10 cable.
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30 **HERE FIGURE 8**

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34 **HERE FIGURE 9**
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42 System OS1 stopped the block successfully, but at the expense of structural
43 integrity: the outer posts were bent significantly and, in the trial runs, some of
44 the anchors were pulled out suggesting that special attention will need to be
45 given to the design of the foundations.
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52 The end connections of the cables that are hit directly can also sustain some
53 damage. Intermediate cables can be used to reduce the maximum deflection
54 upon impact for cases where the barrier is close the infrastructure. Removing
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these cables, however, significantly reduces the damage to the structural elements while allowing only an extra 20 cm of deflection. From a practical point of view, not having to install the intermediate cables also reduces the installation time and cost.

4. Multi-scale considerations for energy absorption capacity

In a preliminary step of the research, some free fall tests were performed on chainlink meshes (Mesh-OS and Mesh-G), 2.5 m by 2.5 m, which were anchored to a frame on all four sides. These tests are not presented herein for the sake of brevity, but the reader is invited to refer to Buzzi et al. (2011) for more information. These tests highlighted the importance of the boundary conditions on the performance of the mesh. Indeed, stiff boundary conditions allow little deflection of the mesh upon impact, which generate high stress in the mesh. It was found that Mesh-G failed at energy levels much lower than Mesh-OS, which was somewhat surprising considering their inherent mechanical properties. Following this observation, we propose to study the energy absorption capacity further from a multi-scale perspective.

Different elements of the system contribute to its compliance and hence its capacity to absorb energy. At the micro-scale, the latter comes from the mechanical properties of the steel constituting the wires of the mesh (see Figure 2a). At the meso-scale, the type of mesh and the deformability of the cells (diamond, hexagon) start to play a role (see the distorted zone in Figure 5b).

1 Finally, at the macro scale the boundary conditions and the breaks/dissipators
2 are contribute significantly to the capacity to absorb energy. The list is not
3 exhaustive and other elements could contribute at the various scales.
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10 The tests conducted on a 2.5m per 2.5 m meshes, as well as the full barriers,
11 suggest that the three levels of capacity to absorb energy are not always
12 mobilized, thus giving rise to different performances at different scales. This is
13 illustrated conceptually in Figure 10. At the micro-scale, which corresponds to
14 loading in tension of a single wire only, the mechanical properties of the steel
15 prevail and Mesh-G performs better than Mesh-OS. At the meso-scale (2.5 m by
16 2.5 m tests), Mesh-G is very stiff while Mesh-OS unravels locally and
17 consequently deforms highly, leading to a better absorption capacity. At the
18 macro-scale, the whole system is critical and governs the capacity to absorb
19 energy.
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37 It is difficult to draw the line between the different scales, but the micro- and
38 meso-scales are more likely to be mobilised in case of “bullet” types of impact
39 (see Figure 10b), whereas the macro-scale capacity is the one that is typically
40 designed for. The practical significance of this concept could lie within the
41 determination of a minimum length, for a specific type of mesh, to mobilize the
42 maximum energy absorption capacity.
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54 **HERE FIGURE 10**
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59 **5. Conclusions**

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2 This paper compares the performance of four different systems designed for 35
3 kJ of impact energy (2 products designed by rockfall specialised companies – G
4 and M -, one designed by the Roads and Traffic Authority – OS1 -, and one
5 empirical modification of OS1). The impacting block (665 kg of mass) was
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7 stopped by all four systems but system G was the only one not to sustain any
8 damage apart from permanent deformation of the mesh. During these tests, the
9 stiffness of the systems was estimated from load – deflection curves and
10 correlated to the loads transmitted to the structural elements. The results
11 showed that the two commercial products, although inherently different in
12 nature, had similar low stiffness. The mesh of these two barriers was highly
13 loaded and absorbed a high portion of the energy. In contrast the system OS1,
14 which includes intermediate cables, may prevent the mesh capacity from being
15 fully mobilised as load is transmitted directly to the posts and foundations. This
16 caused damage to the structural elements.
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40 The performance of system OS1 can be improved by removing the intermediate
41 cables and placing the mesh downhill with respect to the posts. Some damage is
42 still sustained by the mesh upon impact, but the structural elements are not
43 loaded as highly. Indeed, smaller post sections may be used satisfactorily.
44 Removing the intermediate cables significantly reduces the installation and
45 maintenance time, as it is simpler to replaces patches of chainlink mesh than
46 posts and/or foundations. Intermediate cables tend to be used if the barrier has
47 to be positioned close to a passageway. However, it was found that the barrier
48 deflection upon impact only increased by 20 cm in the absence of the
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intermediate cables. Finally, some observations were made on the multi-scale aspects of the energy absorption capacity of a typical barrier.

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Figure 1: (a) Sketch of the cross section of the testing set up: pendulum, optical beam and barrier. (b): Photograph of the set up. The white lines represent the swing arm (right) and the crane chain (left). (c): Sketch of the plan view of the set up.

Figure 2: (a) Stress strain behaviour of the material constituting the three different meshes. (b) View of the chainlink Mesh-OS. (c) View of the chainlink Mesh-G. (d) View of the composite double twist Mesh-M including the undulating 7 mm cable. The mesh is connected to the top cable via a 7 mm lacing cable.

Figure 3

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(a)

(b)

Figure 3: (a) Load cells used to measure the load on the cables and (b) on the anchorage of the posts.

Figure 4

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Figure 4: Evolution of the block velocity from impact estimated by the image tracking software (continuous line) and the best fit (dashed line) for test on system G.

Figure 6

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Figure 6: Evolution of the equivalent static force vs. deflection of the system from the moment of impact for the four systems.

Figure 7

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Figure 7: Evolution of the force recorded by a load cell in the top cable during test on system OS2. 500 data points every 0.2 s.

Figure 8
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Figure 8: (a) Forces recorded at the base of the posts 3 and 4 and (b) on the top/bottom cables as a function of the stiffness of the system. Due to technical issues, the load cell at the base of post 4 for the system G did not record any data. Similar problems occurred with the load cell inserted in the bottom cable of system OS1.

Figure 9

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Figure 9: Damage to post 4 for system OS1 after impact and the loads recorded in the cables.

Figure 10: (a) Conceptual evolution of the capacity of the system to absorb energy as a function of scale. (b) Evidence of a “bullet” type of perforation. Photograph taken in New South Wales by the authors.