Horizontal and slanting reinforced concrete slabs for structurally dissipating rock-shed: experimental analysis

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ABSTRACT: The aim of this paper is to (i) present a new concept of Structurally Dissipating Rock-shed (SDR), (ii) analyze experimental behavior of SDR-slabs under impact load. The analysis is done for two reinforced concrete slabs: a horizontal slab (12m x 4.8 m x 0.28m) and a slanting slab (8m x 4.8m x 0.28m) that both represent reduced slabs (1/3 scale). The analysis (for rock fall energy about 135.10^3 joules) points out the main mechanisms of deformation and the effect of the sloping of SDR-slabs under impact load.

Keywords: rock fall, impact load, reinforced concrete, dynamic behavior, slab damping.

1 INTRODUCTION

Among the well-known risks in mountain area, there are accidental rocks falls. They often have damaging effects (unusable road or rail network, damaged infrastructures, …), which could greatly affect the economic development of towns and cities in mountainous regions. With regard to the rock fall risks, the main preoccupation of decision-makers and users is the safety and the uninterrupted use of the ways of communication.

The problem of safe ways in mountainous region is usually dealt with putting (i) protective nets in regions exposed to the rock falls, or (ii) protective rock-shed.

A usual technology of a protective rock-shed (Montani 1998), (Masuya et al. 1999) consists in achieving protective structure on which thick bank-run gravel is put. The bank-run gravel acts as dampening material, which aims to absorb the impact energy. Consequently, the design of such structures is based on static and normative considerations.

The main problems of this technology are:
(i) the needs for important foundations due to the heavy weigh of the structure. Unfortunately, such foundations are difficult and expensive to achieve in area with frequently poor bedrock quality and
(ii) the safeguarding of the protective rock-shed (removal of fallen blocks, changing of bank-run gravel, repairs, …).

To add our contribution to safety ways in mountainous area, we have recently, developed, (Tonello 1986), (Delhomme et al. 2003) (Mougin et al. to be publish) another concept of protective rock-shed called the SDR concept. In contrast to the usual technique previously described, the dissipation of impact energy is done through the slab and their supports.

The aim of this paper is to (i) present the Structurally Dissipating Rock-shed (SDR) concept, (ii) show the experimental behavior of the SDR-slabs and (iii) compare tests carried out on a horizontal and slanting reinforced concrete slabs impacted at “Equivalent Ultimate Limit States” (EULS) conditions.

In sections 2 and 3 we recall the SDR concept and present some experimental results. Section 4 analyses experimental results, compares and point out the dynamic effects in impact behavior of SDR-slabs.

2 STRUCTURALLY DISSIPATING ROCK-SHED (SDR) CONCEPT

The new idea developed with the concept of structurally dissipating slab comes from the two main functions assigned to the rock-shed slab and their supports:

- absorbing impact energy through the slab motion and the damage of the concrete when the shock occurs in middle area,
- crashing and plastic behavior of the supports of the slab.

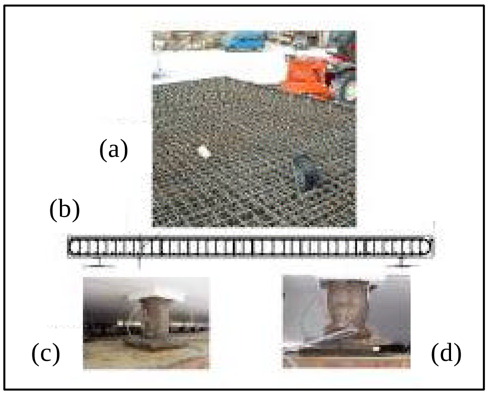

Figure 1. (a) Reinforcement steels of SDR-slab, (b) cross-section of SDR-slab on its supports, (c) Undamaged support, (d) Support damaged by impact load on slab side.

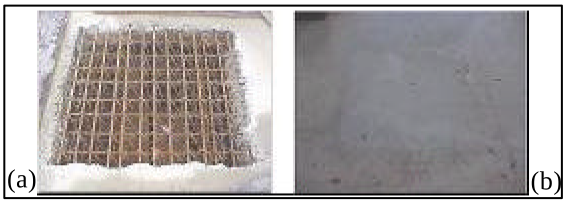

Figure 2. (a) Damaged concrete removed by a high-pressure water jet (hydro demolition) (b) repaired slab.

The originality of this concept is to find solutions to the two functions above without a need for bank-run gravel over the slab. Therefore, we realize and design the SDR-slab (thickness, steel reinforcement, …(Fig. 1a, b)) in order to absorb the impact loads by bending deformation in elastic domain (deformation without great damage for usual rock fails). About the impacts on the slab sides, we realize specific steel supports (Fig. 1c), which aim to absorb impact load by their plastic and crash deformation (Fig. 1d).

In addition to the weight reduction of the rock-shed, this concept could allow easy repairs. Indeed, for local impact damage in the middle area, the damaged concrete can be removed (Fig. 2a) by a high-pressure water jet (hydro demolition). Then the concrete can be rebuilt (Fig. 2b) after changing the broken reinforcement steels. About the impact on the slab sides, the repair could consist in a simple change of damaged supports (Fig. 1d). Besides, for weak impact energy, the slab behaves in its elastic domain leading to lower maintenance coats of the protective rock-shed.

3 EXPERIMENTAL IMPACT BEHAVIOR OF SDR-SLAB

3.1 *Experimental procedure*

The experimental analysis consists in simulating rock falls on slab made according to the SDR concept. The tests intend to drop a block of 450 kg or 800 kg (Fig. 3-a) from a given height in order to obtain a fixed energy (135.10^3 or 320.10^3 joules). For the energy of $135x10^3$ joules, the block is dropped from 30 m. The block velocity just before impact is about 24.5 m/s. The impact energy (E) and block velocity (v) just before impact are approximated by mean of relation:

$$E = Mgh = \frac{1}{2}Mv^2 \qquad (1)$$

with $v = \sqrt{2gh}$

where M, g and h are the mass of block, field of gravity and the height of the fall, respectively.

The block is lifted to the dropping height by a crane (Fig. 3-a, 3-c). A specific device (Mougin et al. to be publish) allows to drop the block without any initial speed. The block is fitted out with accelerometer and crash test checkerboard (Fig. 3-a) is attached on the block in order to allow the analysis with a high-speed camera.

Two slabs have been tested: a horizontal slab (12m x 4.8 m x 0.28m; Fig. 3-c) and a slanting slab (8m x 4.8m x 0.28m, slab slope 45°; Fig. 3-b) that both represent model slabs on the scale of 1/3 scale. The horizontal and slanting slabs are respectively made of B30 and B35 concrete. The reinforcing steel bars are 8 mm in diameter for shear reinforcement (vertical reinforcement), 14 mm diameter for longitudinal reinforcement and 16 mm diameter for cross reinforcement. The steel bars have an average modulus and an elastic yield stress respectively equal to 200 GPa and 500 MPa. The reinforcement steel ratio is approximately 270 kg of steel bar per 1 m^3 of concrete.

For a complete analysis of impact behavior, we have fitted out the slabs with many sensors like: (i) strain gages, initially fixed on reinforcement steels, (ii) LVDT transducers (Fig. 3-d), used to measure the bending displacement as shown in Figure 4, (iii) specific stoneware clay devices developed (Mougin et al. to be publish) to determine maximal displacements, (iii) accelerometers placed under the slabs and close to the LVDT transducers,

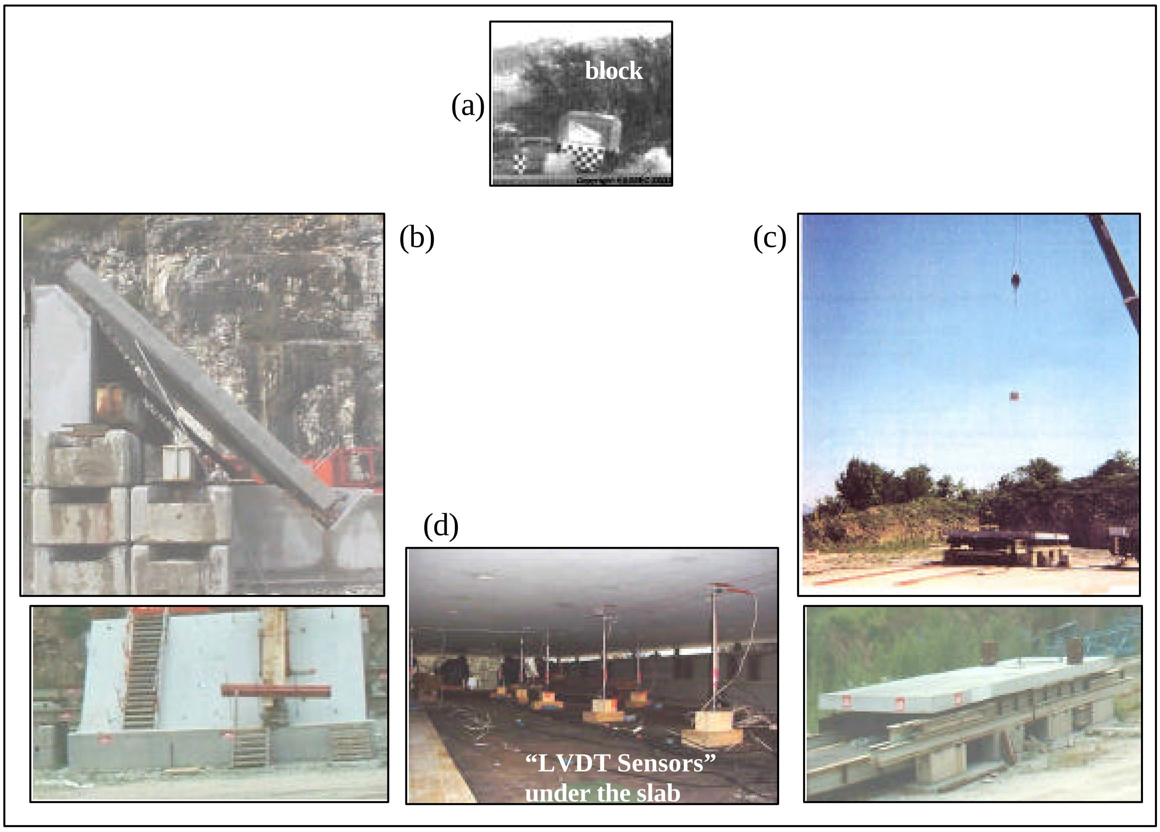

Figure 3. View of: (a) block, (b) slanting slab, (c) Horizontal slab and (d) Displacement transducers (LVDT) situate under the slab.

(iv) strength load transducers located close to supports and (v) a high speed camera for the analysis of the events which occur at the point of impact.

The results presented in this paper concern rock fall tests done under Equivalent Ultimate Limit States (EULS) conditions (rock fall energy about 135.10^3 joules).

3.2 *Experimental results*

For consistence of this paper, we’ve chosen to analyze only the bending behavior and the results of the damage to the two slabs. Therefore, the results presented concern the tests carried out for 30 m high block fall on horizontal and slanting slabs. These test conditions corresponds to (EULS) conditions (135.10^3 joules) of the reduced rock shed slabs.

3.2.1 *Bending behavior*

The tests are done in two areas of the slabs mark on Figure 4-a by square and circle charts. The references to the LVDT transducers are square charts in area 1 and circle charts in area 2. We call (X_1 to X_4) and (Y_1 to Y_3) the transducers in the direction of slab length and width respectively (Fig. 4-a). The transducer close to the point of impact is referred as I.

Figure 4 presents the typical curves in area 1 and 2 of horizontal and slanting slabs. These curves show the bending displacements versus time at three different points of impact: (I_{L2}) impact on slanting slab at point, which correspond to dark circle on Figure 4-1, (I_{H1}) and (I_{H2}) impact on horizontal slab at point, which correspond to dark square and circle respectively on Figure 4-1. The Figure 4-2 shows an extending of the curve (I_{H1}).

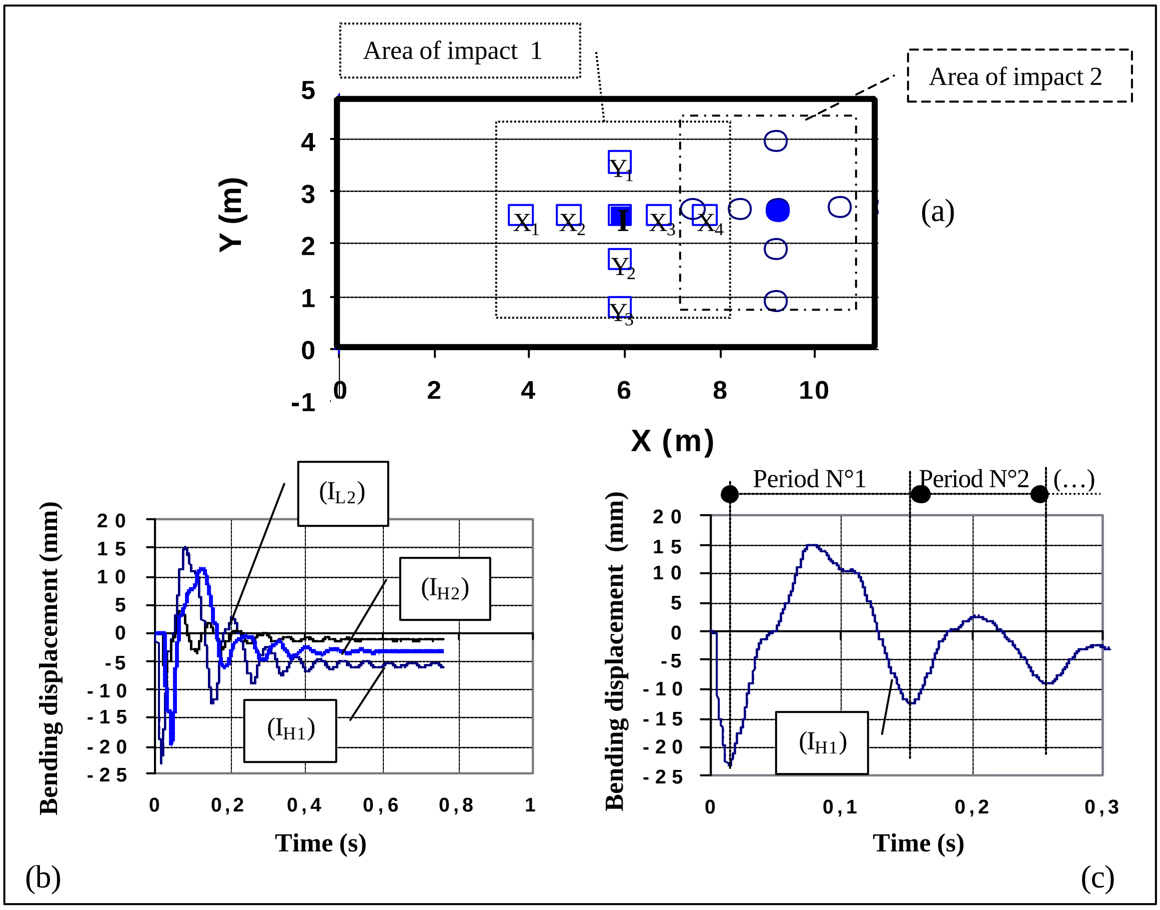

Figure 4. Localisation of displacement (LVDT) transducers and typical experimental displacements at the point impacted. The subscripts H1, H2, L2 correspond to tests on horizontal slab in area 1 & area 2 and slanting slab in area 1 respectively.

The curves on Figure 4 are similar to those often obtained when studying the vibration of dampening structures. The detailed analysis and discussions about these curves are presented in section 3.3.

3.2.2 *Damage and failure*

The cracks due to impact loading are presented in Figure 5. As expected for an impact at 24.5 m/s, the cracks are significantly more important in the horizontal slab than in slanting one. Indeed, in the slanting slab, only a part of the impact energy contributes to damage of the concrete (crack, failure, …). The other part of the impact energy generates tangential loads in the plane of the slab. Due to this tangential load, the slab supports have to be designed and placed correctly in order to withstand these tangential loads. The improvement due to slanting slab is visible as the concrete cracking is limited and natural ejection of the blocks is made possible.

The comparisons of cracks in our tests with those obtain in similar tests carried out in a laboratory (Tsubota et al. 1998) show different failure results of the concrete. Tsubota et al. (1998) have tested a slab 2.4mx2.1mx0.2m) at 2m/s using a high-speed hydraulic set-up. In our tests, we obtain star-shaped cracks whereas Tsubota et al. got cracks, which propagate mainly along the length of the slab. This difference could be due to:

(i) the scale factor effects; the SDR-slab tested is nearly twice as large as the one tested by Tsubota et al.,

(ii) the applied boundaries conditions on the slabs; simple supports lengthwise on lengthways or four corners simple supports of the slab,

(iii) loading conditions; loading close to the actual solicitations or impact in the laboratory with hydraulic set-up.

The star-shaped cracks (Fig. 5-a) are due to our loading and boundary conditions, which are closed to the used conditions of the slab. These conditions are difficult to obtain with laboratory set-up.

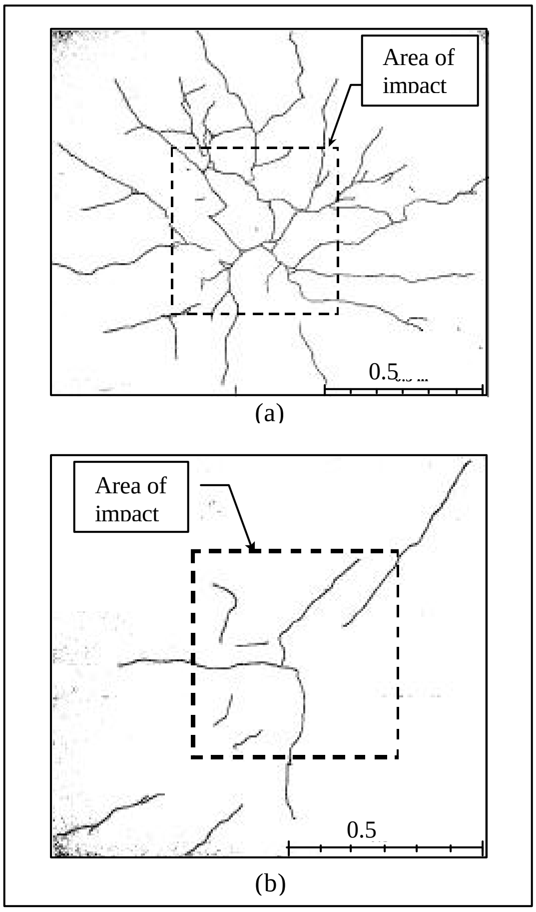

Figure 5. Typical cracks under the point of impact: (a) Horizontal slab and (b) slanting slab.

3.3 *Analysis and discussion of the results*

3.3.1 *Deformation mechanisms of SDR-slab under impact loading*

The curves presented (Fig. 6) could lead to several comments on the experimental behavior of SDR-slabs. Here are two:

(i) One can observe (Fig. 4-b) that the final values of bending displacement are not equal to zero. The analysis of strain measure in steel shows that the reinforcement steel bars didn't reach their elastic limit for tests under EULS condition (E = 135x103 joules). Therefore, the effects of the non-zero value of displacement is due to the micro-cracks in concrete, which load reinforcing steel bars and create such final displacements (Fig. 4-2). The value of the final displacement is more important for the horizontal slab than for the slanting slab. These observations are in agreement with the damage and failure analysis presented in previous section. The limited micro-cracks in the slanting slab lead to slight shift (non-zero value) of bending displacement at the point of impact.

(ii) A qualitative analysis of curves (Fig. 4) shows that the apparent displacement period first decreases and bottoms out (Table 1). The Fast Fourier Transform analysis confirms this observation, which shows that two principal vibration modes could control the deformation of the SDR-slab. The variations in the period of the bending displacements can also be observed through the discontinuity on the curves as shown in Figure 4-c. These discontinuing lines could be due to the two principal vibration modes according to which the SDR-slab would vibrate. Therefore, the displacement, which takes the following form in general case:

$$u_z(x,y,z,t) = \sum_j \sum_i g_j(x,y,z)\, f_i(t).\sin(v_i\, t) \quad (2)$$

could be approximate, at the point of impact, as follow:

$$u_z(0,0,0,t) = A.\left(e^{(-kt)} . \sin(v_1 t) + f_2(t) . \sin(v_2\, t)\right) \quad (3)$$

In the equation (3), the origin of reference (x,y,z) is located under the point of impact (point where the LVDT transducer is placed).

Constant k has to take a great value in order to gives $e^{-kt} \sim 0$ after a few microseconds and let the bending displacement equal ($f_2(t).\sin(v_2\, t)$) later.

Table 1. Apparent displacement periods during the 8 first oscillations.

Point of impact	Period N°1$^{(*)}$ (s)	Period N°2 $^{(*)}$ (s)	Period N°3 (s)	Period N°4 (s)	Period N°5 (s)	Period N°6 (s)	Period N°7 (s)	Period N°8 (s)
I_{L2}	0 .082	0.080	0.093	0.088	0.082	0.100	0.093	0.088
I_{H2}	0.143	0.105	0.076	0.067	0.064	0.061	0.061	0.051
I_{H1}	0.146	0.103	0.069	0.083	0.066	0.066	0.069	0.069

$^{(*)}$ see Fig.4-c.

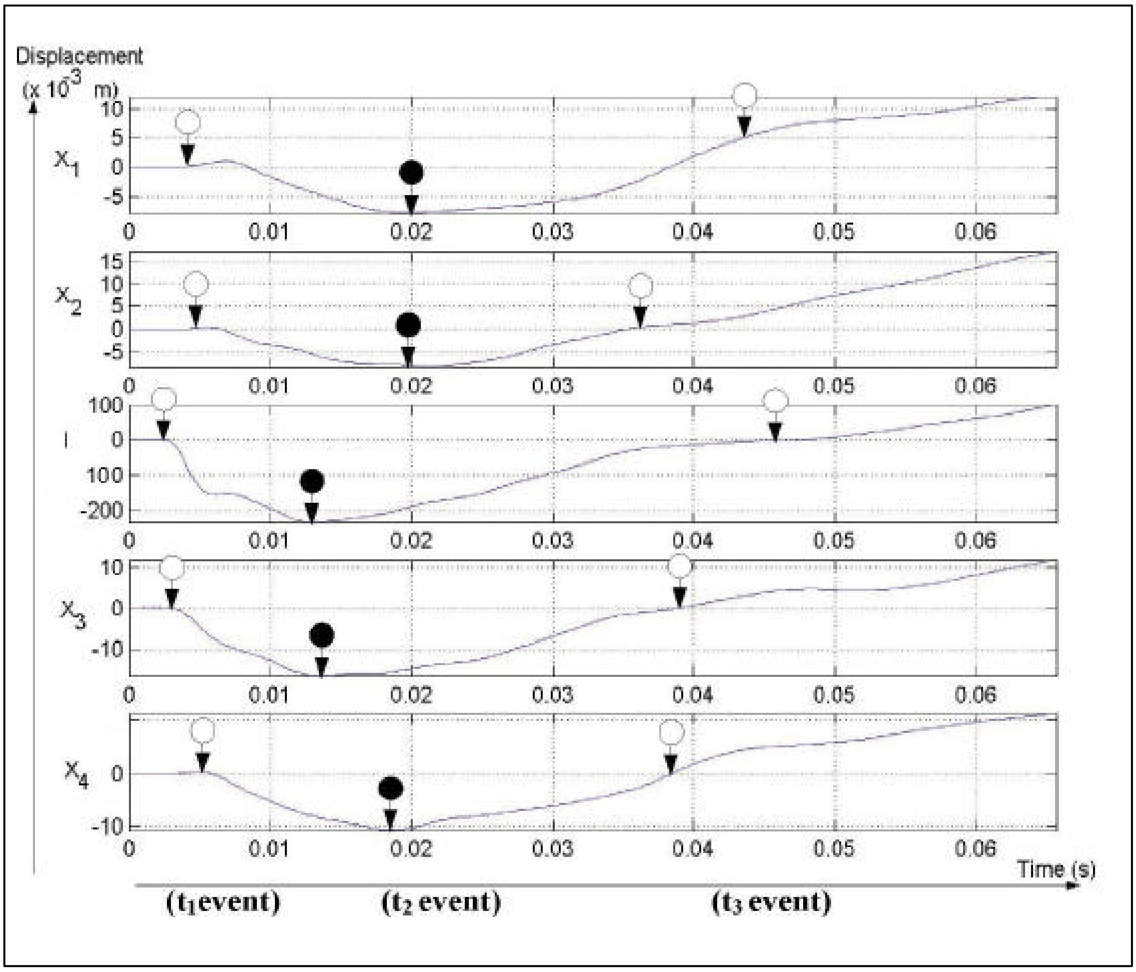

Figure 6. Typical velocity effects during the first half-period. Impact behavior of a horizontal SDR-slab. Impact point (I) in area of impact 1.

3.3.2 *Velocity effects in impact load on SDR-slab*

The aim of this section is to point out the experimental dynamic effects due to impact velocity during the first half-period of slab bending.

We analyze the bending displacement of LVDT transducers X_1 to X_4 (lengthwise transducers). The results of the analysis presented in Figure 6 are similar to those obtained with transducers Y_1 to Y_3 (transducers along the width; Fig. 4).

Figure 6 shows the starting times of particular events occurring in the slab: (i) starting time (t_1) of slab deformation, (ii) time (t_2) to reach the first maximal or minimal displacement, (iii) time (t_3) to get back to zero displacement. In static analysis all such events occur at the same time.

One notes here a significant shift in the occurring of the same event. This illustrates the existence of a time dependence (inertia) phenomenon. The simple way to describe this inertia effect can be summary as follow: for impact velocity about 24.5 m/s, before the SDR-slab supports start reaction, the slab deforms at the point of impact. This unusual phenomenon in classic design of reinforced concrete structures must be took into account for optimized modeling.

4 CONCLUSION

Building safe road in regions where rock falls or avalanche risks are major concerns has been one of the most interesting civil engineering topics in the recent years.

In this paper we’ve presented our recent research on this topic, which has led us to develop a new concept called the Structurally Dissipating Rock-shed (SDR) concept. This concept consists in building a flexible structure that dissipates energy of rock falls. The key element of the SDR-concept concerns the design of the slab in order to dissipate impact energy through both elastic deformation and concrete damaging of the slab or plastic deformation of purposefully designed supports.

This paper has also presented experimental analysis of bending displacements and damage to slanting and horizontal SDR-slabs under the Equivalent Ultimate Limit States (EULS) of impact loading (135.10^3 joules). Based on experimental results, we describe how SDR-slabs can deform and damage.

The results show that two principal vibration modes could control the deformation of the SDR-slab. One of these two vibration modes is soon disappears (some microseconds) and the period of the second one remains constant until the end of the impact. A combination of the vibration modes coupled with the velocity effects analyzed can create loading conditions, which can cause unexpected failure. Therefore, in the modeling and design of the SDRS-slab, particular attention must be paid to dynamic and inertia effects. These effects are similar to those observed on traditional mechanical structures impacted at high strain rate.

The experimental analysis also point out the damaging mechanisms of impacted SDR-slab. We've compared typical behaviors of the horizontal and slanting slabs and finally indicated some parameters that must take into account in the modeling SDR-slabs: (i) the local impact damage, (ii) the dynamic and velocity effects and (iii) the boundary conditions on SDR-slabs (especially boundary condition able to carry up tangential load stresses).

These results add to previous works (Tonello 1986), (Perrotin et al. 2002) yield to validate the concept of SDR-slab and show that it is possible to achieve protective rock-shed without dampening bank-run gravel, when slab is correctly designed.

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