BACK-ANALYSIS OF METAL MICROSTRUCTURES' BEHAVIOUR FOR ORIGINAL EXPERIMENTAL MEASUREMENTS AND ASSESSING OF SNOW AVALANCHE ACTION ON REAL STRUCTURES

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ABSTRACT: New experiments are conducted on the French Cemagref full-scale experimental site in Lautaret Pass in order to improve knowledge about the action of a snow avalanche against structures. The main objectives are to provide realistic and general pressure distribution models usable for civil-engineering design and to replace current restrictive hypotheses in this field. The experiment principle is original, based on the back analysis of structure's behaviour and eventually damages: That means to quantify avalanche action from its consequences on realistic structures rather than from sensors placed directly in the flow. This approach is particularly useful for taking into account the mutual influence of flow and obstacle and for confirming that the result is truly the action experienced by the structure. This approach is also promising in that it ensures the coherence of the method with the tools usually used in mechanics or civil engineering design.

Keywords: avalanche action, space-time pressure profile, back analysis, fuse structure.

1. INTRODUCTION

In mountainous areas, protection against avalanches is an important issue for the safety of infrastructures, buildings and human beings (McClung and Schaerer, 1993). Mechanical solutions make it possible to design adequate structures subjected to dynamic loads, using, for example the finite element method with explicit temporal scheme and realistic material behaviour models (Berthet-Rambaud and others, 2003). Building these structures and providing better protection is also technically possible. But knowledge of the action characteristics is required for a consistent approach.

However, research has not yet fully apprehended the action of the snow avalanche and its effects. Pressure values have effectively been measured and published, for example in (Lang and Brown, 1980) but these data have not been completely exploited for the specific purpose of civil-engineering design, especially in the particular context of real structures subjected to avalanches: answers for real structures in the flow are missing. Then, certain phenomena such as the appearance of a stagnation zone upstream of the obstacle (Faug and others, 2002), are rarely taken into account. Moreover, the obstacle's influence on the avalanche flow and consequently it action, cannot be accurately estimated when sensors and shaped supports are the sole measurement devices.

Practically, this had led to the continued use of equivalent static pressure to design infrastructures subjected to avalanches, even if it is clearly a dynamic phenomena. Moreover, we can show with appropriate numerical tools, that the time evolution of the load during the rush can be largely prejudicial for effective behaviour and strength of rigid structures. The final objective of this new investigation is to study the characteristics of avalanche's action against an obstacle and finally to provide realistic space-time pressure models usable for civil-engineering design.

2. EXPERIMENTAL PRINCIPLE

To reach this objective, realistic buildings should be ideally used in the flow. Instead of sensors providing local information, deformation measurements (and eventually observation of damage) on a macroscopic scale would then provide the best indicator of the loads generated by a snow avalanche. Indeed, these global effects are representative of the complexity of the avalanche action to which the structure is effectively subjected. This action results in particular of the mutual influences between this obstacle and the flow.

However, quantifying the avalanche action and linking this scientifically to the macro-effects caused by the avalanche to the structure is difficult. Such an indirect approach also requires a

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particular study of the behaviour of a structure, using powerful numerical tools and laboratory tests. This part of the investigation is crucial for the quality of the final results and is based on back analysis techniques in the field of mechanics.

It is thus necessary to find the best compromise between the desired precision of usable pressure models in the civil-engineering context and the means available. For example, building an experimental house in a natural avalanche site is of no interest: firstly, the question is not the action that a particular building is subjected to, but it is to obtain general space-time pressure models in typical cases such as a wall in front of the flow. Secondly and without considering costs, it would be very difficult to exploit the behaviour of such a structure when appropriate experimental systems can provide similar results.

To be usable and useful, our approach requires adapted experimental structures that combine representativeness of real buildings and simplicity in order to facilitate behaviour interpretation and application. In this paper, we show the usefulness of very simple aluminium plates, used as macro-sensor and eventually fuse.

Another advantage making this approach such original is that it ensures the coherence of the method with the tools usually used in mechanics or civil-engineering design: precision and quality of pressure models thus obtained will provide consistent data for further structure design in the field of avalanche protection.

To sum up, the proposed principle quantifies avalanche's action from its consequences on realistic structures rather than from sensors placed directly in the flow. The experimental structure becomes itself a macro-sensor and measurements consist in characterizing what it undergoes.

3. SITE AND EXPERIMENTS

3.1 A new experimental campaign on Lautaret site

The first experiments using the method explained in the section above were set up in December 2002 to investigate winter 2002-2003 avalanches at the French Cemagref full-scale experimental site in Lautaret Pass. This site is well known by avalanche specialists because of its long experimental history since 1973 (Issler, 1999). It comprises a total of eight avalanche paths on the different faces of Crête de Chaillol (2600 m max) and two of them are released artificially for safety. This site is also easily all-winter accessible and has a complete experimental infrastructure.

Avalanche path number 2 is especially equipped with an automatic gas release system and a reinforced-concrete shelter with electricity that has been constructed directly at the side of the avalanche path for instrumentation. A 4.0-m-high tripod support is situated in the track and is connected to this shelter.

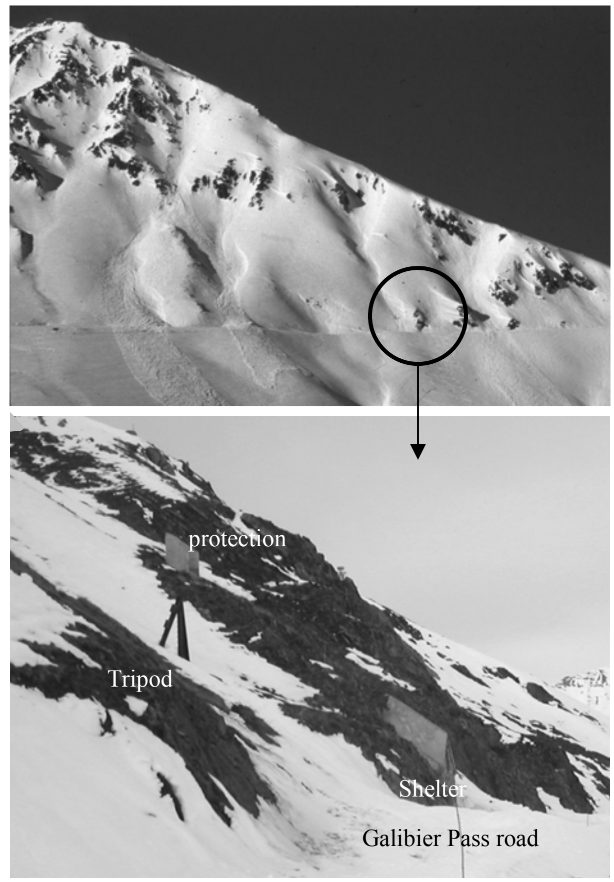

Figure.1: Lautaret avalanche site

Small to medium avalanches occur on this path with sufficient frequency (up to 3 or 4 each winter). Flows are generally dense, wet or dry with sometimes a powder cloud. The run-out distance is 500 to 800 m along a channelled track with an average slope of 36°. Avalanches stop on an open slop at a minimal altitude of 2040 m. Typical released volumes vary from 500 to 10000 m^3.

These characteristics make the site interesting for experimenting with infrastructures or buildings: experiments in this research field are still necessary, and zoning rules generally prohibit direct contact between human society and very important avalanches.

After a several-years low-activity period, a new experimentation campaign at the Lautaret site is organised including new equipments to progressively approach this objective: to obtain realistic space-time pressure models usable for civil-engineering design.

3.2 Measurements from fuse microstructures

According to our experimental principle, the back analysis of metallic targets subjected to a snow avalanche is used to quantify the pressure distribution in the flow. However, the chosen targets must be of a simple geometry to ensure a unique kinematics and hence a unique deformation mode to facilitate the analysis.

Figure 2: Aluminium targets on the tripod

These very simple structures have been dimensioned to have different strengths in order to get a maximum precision. Indeed, the back-analysis of the behaviour of these plates is all the more powerful because deformations are in a representative range: after the flow, some of them can even be damaged with irreversible deflection.

Moreover, some of these indirect mechanical macro-sensors are equipped with a strain gauge to measure temporal evolution of the movements. By using a sufficient number of these structures at different levels in the avalanche, it is then possible to provide information on avalanche action: residual deflections after the flow allow us to determine the maximum pressure vertical profile generated by the flow and gauge signals analysis provides information on avalanche dynamics undergoes by an obstacle.

These metallic targets are placed on the existing tripod in the path. More than fifty fixation points are available at different levels on two sides perpendicularly to the avalanche direction and along the total height of the support (but some of these points are neutralized due to the growing snow pack). Eight data acquisition channels are connected to the shelter at a 4000 Hz frequency.

4. DESIGN OF THE TARGETS

The geometry and the position of the targets in the avalanche flow must guarantee a single deformation mode in order to facilitate the back analysis. We chose a plate structure perfectly clamped at one extremity and free on the others (see figure 3). To encourage the bending mode behaviour and eventually to localise the plastic hinge, the plate's slenderness (L/l ratio) is sufficient to allow cantilever beam behaviour. The width l is arbitrarily fixed in a first step, making it possible to consider the target structures as a pressure cell. The target is positioned perpendicularly to the direction of the flow avalanche at different levels (vertically and horizontally) (see figure 2).

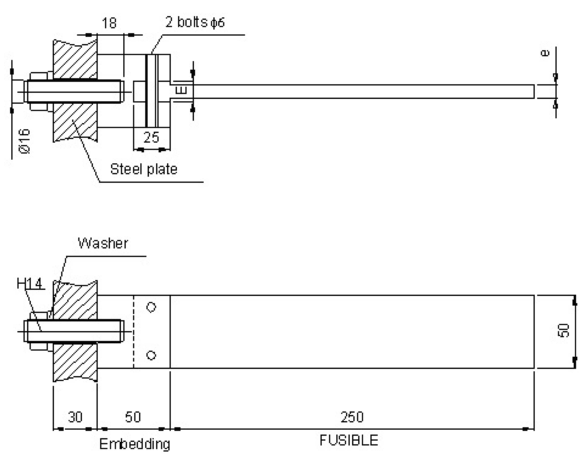

Figure 3: aluminium plate fuse structure

The length and the width being fixed, the thickness parameter e is variable, in order to adapt the resistance to the pressure intensity, which will vary according to the nature of the avalanche (state of the snow) and the elevation in the flow.

The plates are made of aluminium. This material has been chosen in particular because it is now well known that the strain rate sensitivity of its mechanical characteristics is small (of the order of 5%) in the strain rate range between 10^{-4} and 10^{3} s^{-1} (Langseth and Hopperstad, 1996). This is in agreement with data found in the literature (Lindholm et al, 1971) and explains the adequation between crash behaviour of aluminium extrusion under dynamic or quasi-static loads (Abah et al, 1998). This makes it possible to dispense with an additional parameter, making the numerical simulation easier and that is why the strain rate behaviour of the aluminium used here has not been specifically studied.

The material law is obtained via quasi-static tensile material tests. The tensile test specimens complying with the ISO standards, is cut directly in the aluminium plate from which the targets are obtained. The obtained stress-strain mean characteristics are presented in figure 4.

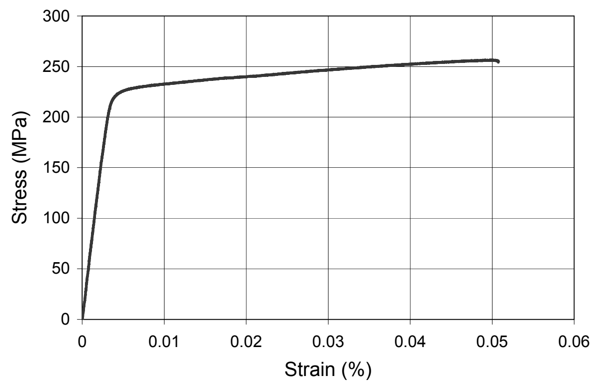

Figure 4: Stress / Strain curve for Aluminium A6060 T5 - direct tension test

Once geometrical and material parameters are chosen, predictive calculations are performed to determine the targets' thickness but also to get a "load-deflection" curve available for each fuse plate. This computational procedure is based on the finite element method, which is now routinely employed in the modelling of structures behaviour in various load configurations. The acceptance of such approaches in the design is continually increasing, due to improved awareness, availability of appropriate software and decreasing computational costs. In particular, simulations must assess precisely the appearance and the development of plastic deformations all the more that, as some targets can notably deform, displacements and rotations, can become so large that an irreversible plastic hinge results.

To perform these simulations, we use the CASTEM 2000 finite element software package. The structure was meshed with triangular DKT (Discrete Kirchoff Triangle) (Batos and Dhatt, 1990) shell elements with three nodes and six degrees of freedom per node. Five integration points are considered across the thickness of each element to evaluate the progressive plasticity effect. The mesh is particularly refined near the boundary conditions, as we knew that this is where the damage (plastic hinge) would normally occur. A non-linear analysis combining large displacements, large rotations, and plasticity is carried out.

Numerically, the material is assumed to be isotropic hardening, and the Von Mises criterion is used for plastic analysis. The load applied to the structure corresponds to a gradually incremented uniform pressure. No interaction is considered between the structure and the load, the pressure is assumed to be conservative (with a constant direction). Figure 5 shows the load deflection curves obtained for different targets depending on the thickness of the plate. Deflections correspond to the maximum displacement obtained at the free end of the cantilever beam.

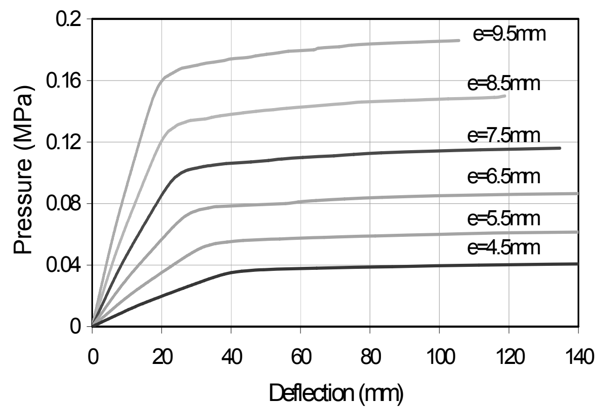

Figure 5: Load - Deflection curves of the targets

These simulations are also used to determine the best place to position the strain gauge on the plate. The numerical analysis of the plastic hinge appearance results in an optimal 1.5cm distance between the gauge main axis and the exterior limit of the embedded zone.

5. LABORATORY VALIDATION OF THE NUMERICAL SIMULATION

To assess the pertinence of the numerical modelling, a laboratory experimental test is conducted on an 8.5-mm-thick fuse plate, similar to those used on site.

This quasi-static bending test is performed using a modified universal testing machine. The boundary condition is exactly the same as on the tripod in Lautaret Site, but instead of a distributed pressure, a local load is applied at the free extremity of the plate. During the test, the direction of the applied load is kept vertical. The target is also tested in a cantilever-bending mode from which the corresponding load-deflection curve is measured.

Then, the same situation is modelled numerically and results are compared to experimental one (see figure 6): The progression of plastic strains in the plate thickness near the plastic hinge appears to be well quantified. This explains the good agreement between the non-linear part of the experimental and numerical curves.

After reaching the ultimate state, corresponding to the yield plateau, the structure is unloaded. This makes it possible to quantify the residual deflection and the elastic springback, which takes place when the load is removed from the structure. The resulting stress release gives rise to elastic deformations. These elastic deformations resulted in less severe overall shape change.

This strain release at unloading, at a point in the structure, is roughly proportional to σ / E, where σ is the stress before unloading, and E is the Young's modulus. The experimental unloading was neither load nor displacement controlled. This explains the variation in the stiffness observed experimentally in the post-critical behaviour. Furthermore, the springback is well quantified.

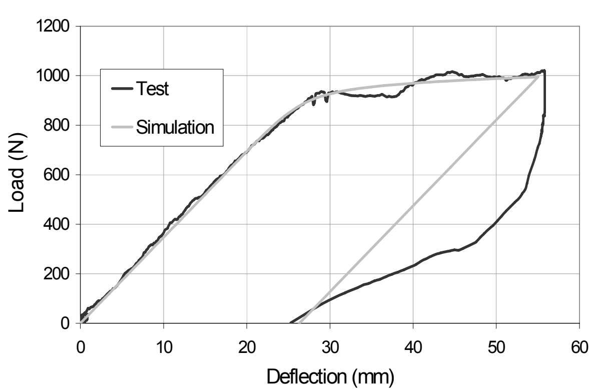

Figure 6: Load - Deflection curves (experimental and numerical) for the 8,5mm thick target laboratory test

Finally, these results for an experimental test representative in kinematics terms (same plastic hinge) confirm that the numerical model of the target is correct. This validation of the numerical simulation means that this indirect approach can be used in particular to quantify the maximum pressure load undergone by a target, back-analysing its residual deflection. In that case, this final deflection after the load release is the critical factor to determine this maximum pressure.

6. EXPERIMENTAL RESULTS FOR MAXIMUM PRESSURE: THE JANUARY 14th 2003 AVALANCHE

Several avalanches were released at the Lautaret site from December 2002, which generated deformations and damage on different targets (note, moreover, that once a fuse plate is deformed, it is changed before the next flow). Among these different attempts and including experimental difficulties linked to the development of a new principle, the avalanche of January 14th 2003 is particularly interesting all the more it is particularly representative of the Lautaret flows.

Figure 7: fuse III-d-b after the January 14th 2003 avalanche

Using the approach described above, first maximum pressure values were produced and are summarized in Table 1 with maximal deflections measured and the associated pressure estimated by numerical simulation as explained previously.

Target	Thickness (mm)	Elevation (m)	Measured maximal deflection (mm)	Numerical estimated maxi pressure (kPa)
IV-d-b	4.3	3.60	28	35
III-d-m	6.47	2.75	153	87
III-d-b	8.5	2.54	61	146
II-d-h	4.56	1.96	221	43
II-d-b	8.57	1.54	53	148

Table 1: Maximum pressure evaluation from some targets damaged by 14-01-03 avalanche.

These results are very interesting and promising for several reasons:

First, measurements of snow density before the avalanche and evaluation of flow speed by video means are respectively about 300 kg.m^{-3} and 30 m.s^{-1}. The usual equation giving maximum dynamic pressure as $P= ½*\rho*v^2$ where ρ is the density and v the speed, gives 135 kPa. This point confirms that our results are not out of mind.

Secondly, targets were pre-designed according to former pressure measurements on the site in the 1970s (Marco, 1994). However, pressures were higher than expected for the avalanche of January 14th 2003. A first glance indicates that results depend on the measurement method (what was already observed, for example by (Lang & Brown 1980)). By its basic principle, our new approach must provide more realistic results than a classic method using pressure sensors because we measure effectively what is undergone by the structure and not what is generated by the natural phenomenon. To confirm this, future experiences will include the comparison with pressure sensor measurements.

Finally, if we plot a vertical pressure profile from Table 1 values, we obtain a very irregular shape. However, considering fuse II-d-h, the maximum value it is able to indicate with its characteristics is less than 50 kPa (see Fig. 5). That means that in the case of a fuse that has been greatly deformed with high deflection, it is no more able to represent the maximum action undergone and the result does not correspond to this maximum pressure but to a low limit of this value. In fact, when deflection becomes too high, the problem can no longer be considered as a problem of normal action on the obstacle but it combines tangential and normal loads. Furthermore, such plates cannot deflect indefinitely and this example shows that fuse targets have to be well adapted and chosen depending on the foreseen pressure range.

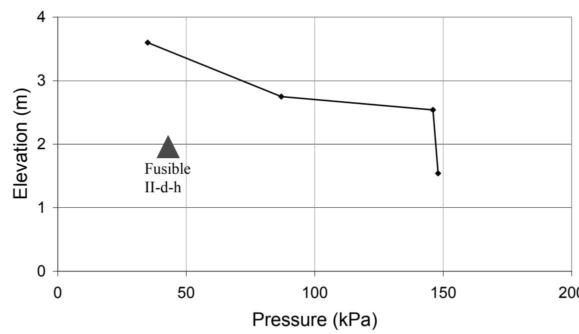

Figure 8: Vertical pressure profile of 14-01-03 avalanche

The problem is then to choose as a preliminary the right thickness: thin enough to be damaged but thick enough not to be completely deflected. Eliminating this particular point, the profile is much more accurate as shown on figure 8.

Of course, these are first results on a single avalanche, which must be confirmed, but the method is very promising and this profile confirms the reliability of this new approach for maximum pressure evaluation.

7. LOCAL STRESS TIME MEASUREMENTS JANUARY 30th 2004 AVALANCHE

Another crucial point to characterize an avalanche action concerns its dynamics. Indeed, the consequences for a structure can be greatly different in particular depending on the pressure increase rate during the rush, even if the maximum pressure value is finally the same (Berthet-Rambaud 2004).

Moreover, the evolution of the action undergone by a structure subjected to a snow avalanche is very badly known whereas it is essential to design and dimension resistant protection. In this context, results obtained from the strain gauges placed on the downhill face of certain aluminium plates are very remarkable.

For dynamics, the studied avalanche occurred on January 30th 2004 after a complex and disturbed snowy period of several days. Finally, the snow pack included a hard layer just thirty centimetres below its surface and the released volume corresponded only to this top layer of dry cold snow.

In spite of this reduced volume, the flow was rather quick (about 90 km/h) with a light powder part in front of a thin dense flow. Next pictures (see figure 9) show clearly the great influence of the "obstacle" (tripod + targets) on the flow and confirm that this aspect is crucial to evaluate the action effectively undergone by a structure subjected to an avalanche. In particular, we can see that the powder part seemed not so disturbed by the tripod whereas its interaction with the dense flow created important vertical jets. Of course, these jets depend mainly on the obstacle shape. The influence of this interaction "flow-structure" appeared also at the end of the avalanche where snow firstly transported had been naturally arranged uphill and around the obstacle to finally change its effective profile and consequently modify avalanche action.

These visual verifications are also to be compared with gauge signals. Due to a thick snow pack before the flow, only the top 1.5m of the tripod was outside and two equipped plates can be exploited. These two plates were deformed with irreversible deflection, which also makes it possible to evaluate the maximum pressure as previously.

Figure 9: Sequence of the interaction of the January 30th 2004 avalanche with the tripod on Lautaret site.

As the inverse analysis for such a dynamic case including material plasticity is rather complex, we only present here (see figure 10) the time-curves of the stress at gauge place. It is not directly the avalanche load but with our philosophy, this evolution shows especially what can be effectively undergone by such a structure in the flow.

These two curves start at the first contact between the powder part and the tripod and correspond respectively to the "right down target" (in black) and " left up target" (in grey). Before the avalanche, the first one was situated on the right just at the snow pack surface whereas the second one was on the left at about forty centimetres above this surface.

These two curves appear radically different whereas they concern the same flow at two close points. The fact that the dense flow is rather thin explains that the left up target stress disappears quite rapidly: this plate is subjected mainly to the powder part. For the right down target, it is also interesting to note that the avalanche continued during about thirty seconds whereas the stress became null already after fourteen seconds: this shows that the snow modification created upstream to the obstacle (eventually including a dead zone) can decrease or even cancel efforts undergone by the structure whereas the flow is still continuing.

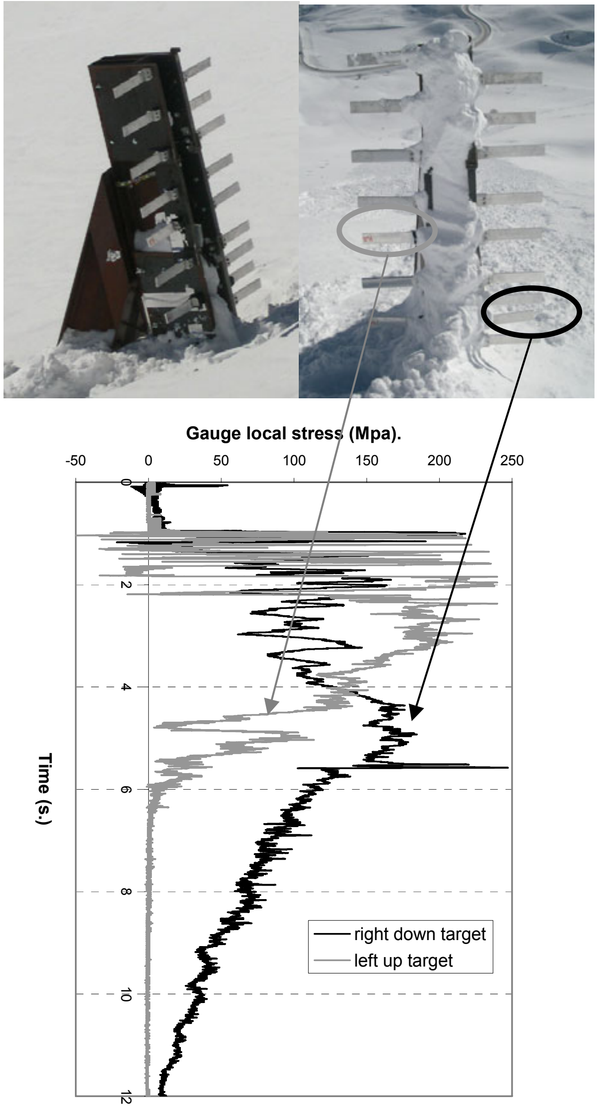

Figure 10: tripod view before and after the flow, gauge local stress curves for two representative plates.

Concerning now the powder and the dense flow, these curves show a great difference: after two seconds, the dense flow generates a quite regular stress mainly with progressive evolutions. In that way, the stress peak occurred for the right down target after 5.5 s may probably be due to a snowball impact.

On the contrary, during the two first seconds, the powder flow generates totally disturbed signals including very short stress increases but also decreases. Detailing this period, very high stress evolution rates can be evaluated with a quick succession of loading and unloading phases surely explained by turbulences. Some of this phases seem even include inverse load cases.

If it is difficult to evaluate a general pressure time-profile directly from this single example, but these results show especially that stresses undergone by a structure subjected to a snow avalanche is highly dynamic and transient, exactly what is especially prejudicial for a rigid structure!

8. CONCLUSIONS - PROSPECTS

One of the first objectives of this new experimental campaign has already been reached: maximum pressure values can be precisely evaluated by back analysis of fuse targets deflection and gauge signals can provide very interesting information about what is undergone by a structure in the avalanche flow. These results confirm the reliability of our back-analysis principle. Furthermore, they underline the necessity to include more consistent hypothesis in structure design and dimensioning for a safer protection against avalanches.

Next season’s developments will use the same principle to study the behaviour of a more realistic structure. The objective is to come closer to the situation of a real building. This structure will consist in a 1m² steel plate placed frontally to the flow on a vertical steel beam fixed in the ground. In the same way and instead of using classic sensors, it will be instrumented with several strain gauges on the embedding beam zone, with one accelerometer at the top.

Using this new approach and synthesizing results from different avalanches and experiments on different sites, we must finally be able to define the main characteristics of the space-time action experienced by a real structure subjected to an avalanche. Moreover, this method warrants that the results are representative of what is effectively undergone. In parallel, this principle could be applied with the appropriate mechanics and numerical tools to simple structures damaged by avalanches such as pylons and walls. Further applications should then ensure a proper connection with the field of structure design and computation, allowing more realistic and reliable loadings to be introduced and safer structures against avalanches to be constructed.

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