RESPONSE TO THE REVIEW #1 OF MANUSCRIPT NUMBER: NHESS-2022-93

We thank the reviewer for these numerous and detailed comments. Responses to these comments are provided below in red.

The article describes the collapse of a large hall with a flat roof in southern France after heavy snowfall turned into rain. The analysis of such cases is very valuable on the one hand to check the design snow loads and on the other hand to identify structural weak points of a structure. The study was carefully prepared, but unfortunately no quantitative data was available on important input parameters such as the amount of snow load at the time of the damage or the condition of the structure before its collapse. Therefore, the main statements of the article are somewhat speculative. In order to finally answer the question what was the exact cause of the collapse of the building, the collapsed structure would have to be investigated in more detail (e.g. material technology tests). In several building collapses, such as the ice rink in Bad Reichenhall, material deficiencies were partly responsible.

We thank the reviewer for their general and insightful comment on our manuscript. We agree that some points were unclear. We will provide a revised version of our manuscript which will (i) better explain the quantification of the rain-on-snow event in spite of the many uncertainties associated with some lack of data (as it is often the case when precise data localized in space and time would be needed) and (ii) provide further simulations based on the FE model of the structure under different pressure distribution conditions, as suggested by the reviewer. No tests of the collapsed materials and/or elements of the structures were made after the collapse, unfortunately. That said, we will provide some additional analysis, thanks to analytical buckling calculations which were found to be consistent with the FE simulations' results and can help to better assess the potential reasons of the building collapse.

The beginning of chapter 1 Introduction has only a small relation to the main content of the article. Dynamic effects of gravitational natural hazards on a building have completely different consequences than static effects such as snow load. I recommend making only a reference to snow loads in the introduction.

We agree that this first paragraph is not closely related to this study and we will follow this recommendation. We will remove the first paragraph and start the introduction by focusing on static snow loads.

The collapse of the building would need to be described in a bit more detail:

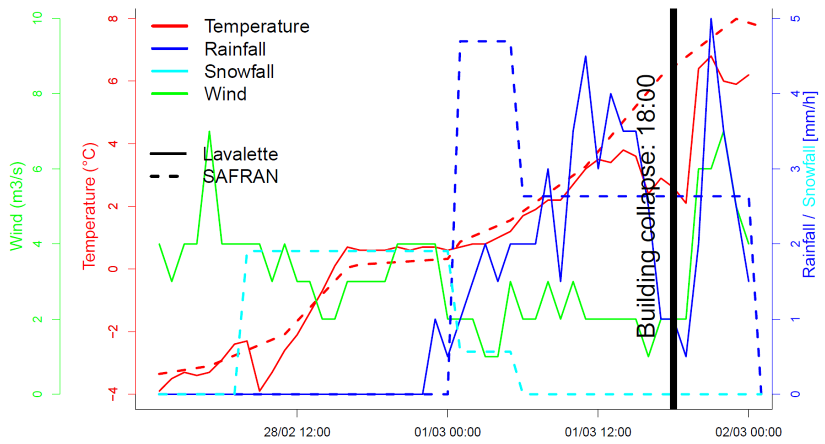
- Time of the collapse?

The collapse took place on 1 March at around 6 pm (Figure 5).

- Weather at the time of the collapse: wind effects?

At the time of the collapse, the temperature was positive and around 2 °C. The intensity of the rain had dropped and was around 1 mm. The wind velocity was 2 m/s. It is noted that during all the day of March 1, the wind was force 1, with a velocity between 0 and 3 m/s. It is therefore unlikely that the wind could have had an effect on the snow distribution on the roof level before and at the time of the collapse.

Figure 5 will be modified and will show the wind measurements at Lavalette:



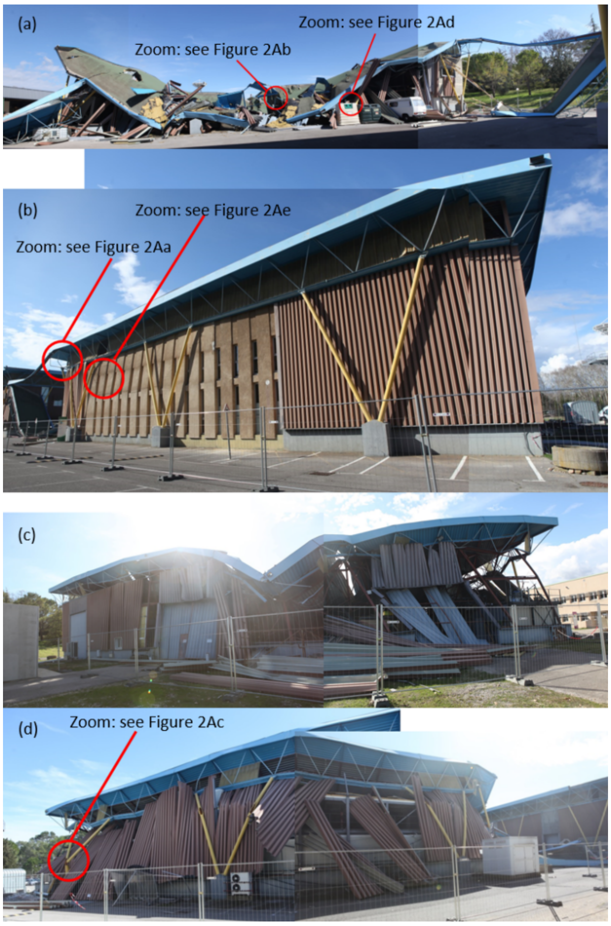
- Snow depth and snow distribution on the roof? Equal amount of snow on the ground as on the roof?

No information on the snow depth and distribution on the roof is available. As the roof slope was low and the wind was only Force 1, we consider that the snow distribution (before the rain) was uniform for simulations. But when rain started to fall instead of snow, the pressure exerted by snow and rain accumulation was probably non-uniform. We have tested two other cases of rain-on-snow distribution and we will present them in the revised manuscript (in addition to the initial scenario with fully uniform pressure distributions). In one case, we assumed that water rapidly flowed on the edges of the roof and in the other case we assumed that water mainly accumulated in the center of the roof. We will present and discuss the consequences of those different scenarios.

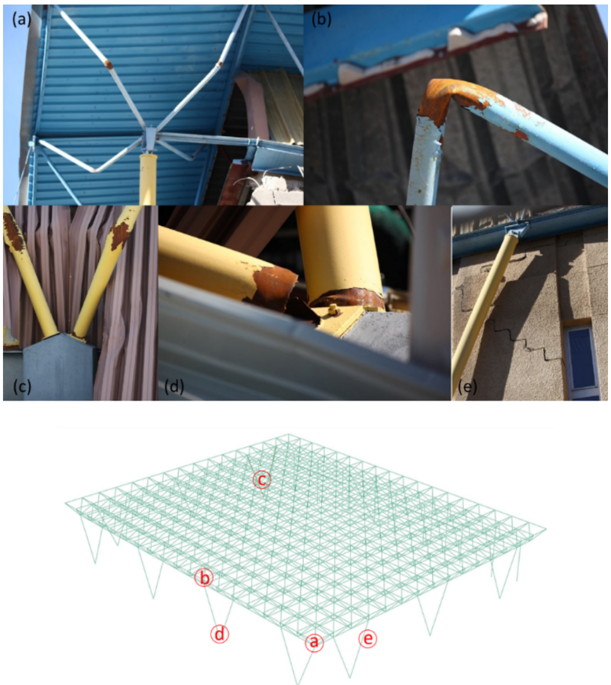
- Overview sketch with details of damage to the structure?

The exact locations of some details about the damages to the structure which are presented in the pictures of Figure A2 are now specified in Figure 10, as shown below, and in an overview sketch inserted in Figure A2.

New Figure 10:



New Figure A2:



- Were there any eyewitnesses?

The entire site was evacuated in the early afternoon of March 1; only the caretaker was on site at the time of the building collapse but he did not observe the snow on the roof. There were no eyewitnesses of the amount or distribution of snow on the roof, unfortunately.

The building and the supporting structure would also need to be described in a more precise way:

- is it a spatial supporting structure (Fig. 7a only shows the truss construction of the supporting structure; Figs. 8 and 11 do not allow to see the necessary details of the truss.)?

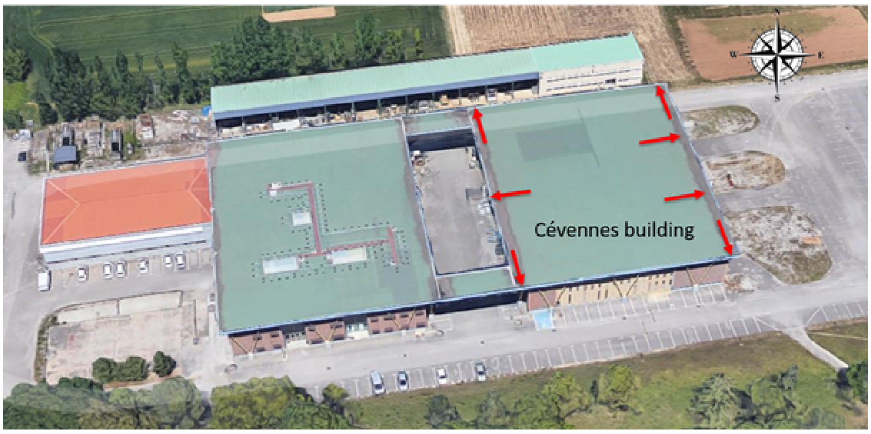
The lattice structure, which withstands all the forces applied to the roof, is indeed a spatial supporting structure that spreads under the entire roof surface.

- Roof pitch according to plan (line 145: nearly flat; line 151: about 1%; Fig. 9: less than 1%? What is the correct slope?)

According to the architect's plans, the roof slope is equal to 1 % on either side of the roof peak line oriented north south.

- Drainage of the roof: location and number of outlets – along the edge of the roof? Were there emergency outlets for the water?

Because of the 1% slope of the roof, rainwater was flowing east or west of the building. Rainwater was supposed to flow along a small wall on the roof perimeter and to be normally evacuated thanks to seven 20 cm high outlets. Four outlets were located at the end of the north and south edges, one at the middle of the west edge and two at quarter and three-quarter of the east edge, as specified by the red arrows in the figure below. All this information about the water drainage system will be added to the revised manuscript.



- Steel properties of the various structural elements - was only S235 used?

The Irstea Cévennes building dating from the 1980s, it was very difficult to obtain the exact design records: neither the calculation notes nor the record drawings could be found; only the architect's plans are now available. We therefore do not know what type of steel the supporting structure was made of and no material testing was carried out after the collapse. We therefore assumed that all the supporting structure consisted of the S235 steel, commonly used in building construction.

- Further, when analyzing a building collapse, comment on the loading history (e.g. max. snow loads since construction, line 329: 42 cm on 22 Jan 1992) and any adjustments made to the building (e.g. alterations to the structure).

Even if the studied building is not located in an area with intense snow events, it had to support heavy loads (at least) three times in the past since construction:

- Around 27 cm on 14-16 January 1987;

- Around 28 cm on the 22 january 1992;

- Less than 10 cm on 7 March 2010.

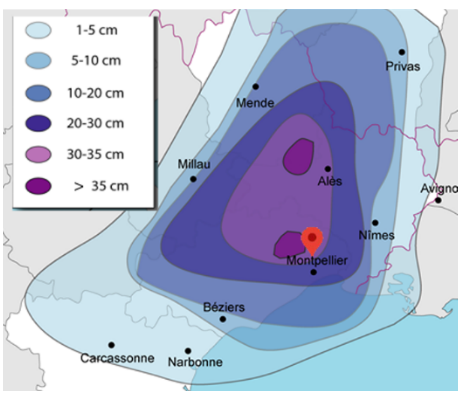
The record of 42 cm in January 1992 was obtained from infoClimat, an association which collects meteorological measurements from various sources (amateurs, photos, etc.). As this record is much higher than the measurement of 28 cm of the station of Montpellier from Météo-France, and does not seem to be corroborated by other sources, we will change this number to the record from Météo-France: 28 cm.

Moreover, no adjustment has been made to the supporting structure from its construction to its collapse. Only interior fittings (mezzanines supported by the ground) were carried out in 2014.

- According to Fig. 4, Montpellier is in the zone with 20 to 30 cm of snow. However, in the following, a snow depth of 30 to 35 cm is used for the analysis: a justification is missing.

The Irstea building is in fact located in the North of Montpellier, at the edge of the purple area with 30 to 35 cm of snow, as shown in new Figure 4. Moreover, a hill separates the city center of Montpellier from the site of Lavalette, which explains the presence of purple areas with greater snowfall north of Montpellier.

The new Figure 4 in the revised manuscript will indicate the site of Lavalette with a red marker:



- The assumed new snow density of 250 to 350 kg/m3 seems too high. I would expect a maximum of 250 kg/m3. It would be interesting if the snow depth and density could be quantified with measurements.

Unfortunately, we have no measurement of snow density. But all local testimonies converge to say that the snow was heavy. We agree that the upper bound of 350 kg/m3 for initial snow density may have been overestimated, but an upper bound of 250 kg/m3 is still likely, especially in the context of a Mediterranean area around Montpellier. A snow density of 250 kg/m3 will be taken into account in the revised manuscript.

- The SAFRAN simulation with a SWE of 35 mm seems plausible.

SAFRAN reanalysis data, as the other sources of information presented in this study, also suffer from several limitations: its spatial resolution, the data being provided at a 8 km x 8 km resolution (l. 121); the available number of gauges used to derive this reanalysis. In this study SAFRAN is considered as an important source of information which complements the snow load map and the measurements provided by the in-situ measurements of the station at Lavalette.

- The consequences of rain on the snowpack should be discussed in much more detail. A 30 cm layer of snow is unlikely to retain 50 to 60 mm of rain. Typically, snow is saturated with about 15% water. The rain that cannot be stored runs off on the roof surface. The assumed "wet" snow density of 600 kg/m3 seems to be too high.

When it started to rain, it is likely that the rainwater outlets were obstructed by the 30-35 cm snowpack already present on the roof. Some of the rainwater could then seep into the snow and settle the snow slightly, and the surplus of water could probably flow towards the east and west edges of the roof, as long as the curvature of the roof due to snow and rain loading has allowed it. At some point, when the curvature of the roof became too important (and counter-balanced the initial 22.5 cm roof height), the rainwater certainly started to accumulate in the center of the roof.

The assumed value of 600 kg/m3 for ultimate snow density was probably misleading. It corresponded to an "equivalent" snow and rain density uniformly distributed over the roof. In fact, the wet snowpack was probably heterogeneous with zones of soared snow at higher density (300-400 kg/m3) than the initial snow (250 kg/m3) and other zones at the bottom with accumulated water (1000 kg/m3) due to preferential water flows. The value of 600 kg/m3 used in this study corresponds to an equivalent value to define the (equivalent) pressure exerted by the combination of snow and rain accumulations. We now try to better account for the heterogeneity of the mixture of wet snow and water, by considering different scenarios of non-uniform pressure distributions in the revised version of our manuscript (see one previous response to the reviewer's comment about this point).

The calculated bearing capacity of the supporting structure seems to be rather high:

- At best, e.g. stability analyses (buckling) of the columns or the tubular truss elements could provide further insights.
- In the damage analysis of a large flat roof after a rain on snow event with questionable drainage, the assumed uniform load distribution is rather simplified. The important question is, where was the water, which could not be absorbed by the snow cover,

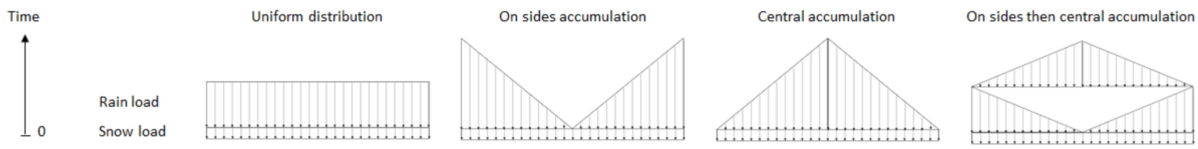
before the collapse? The roof was sloped, I assume that a large part of the water flowed to the edge of the roof. The maximum water load would therefore be along the edge of the roof. This can be simulated with an additional load case with a trapezoidal load distribution (minimum snow/rain load roof center and maximum snow/rain load roof edge).

- The snow load can cause a sag in the middle of the roof, which may be greater than the overheight due to the roof pitch of less than 1°. This would result in the water not absorbed by the snow cover flowing to the center of the roof. This could also be studied with a load case with trapezoidal load distribution (maximum snow/rain load in the center of the roof, minimum snow/rain load at the edge of the roof).

Thank you very much for these interesting comments.

We performed buckling calculations of the columns and the tubular truss elements. They show that the rectangular tubular columns of the east facade are much more sensitive to buckling than the tubular crossbars of the lattice roof and the tubular columns of the other facades. This result is fully consistent with the results obtained with the FE model.

We agree that the assumed uniform load distribution for the total load is maybe too simplistic. However, we think that the distribution of the initial snow load was nearly uniform, because of the low slope of the roof and of the very little wind during the snowfall. Moreover, we also have strong reasons to think that all the rain remained on the roof until the building collapsed since the rainwater outlets were obstructed by the snow depth in place. Experiments performed in a controlled environment at CSTB show that wet snow can lead to a complete obstruction of 30-cm wide outlets (Philippe Delpech, personal communication). Rain can theoretically seep first into snow until the water saturation rate of snow is reached ; here, we do not consider infiltration as the initial snow density was already high. So, rain likely accumulated first on the west and east edges of the roof until the direction of the roof slope reverses due to the roof curvature increase. After that, rain accumulated in the center of the roof. So, rather than only considering a uniform distribution for the total load, we propose to study four different cases of loadings (see figure below) for snowfall heights of 30 and 35 cm. The results corresponding to those different scenarios will be presented and discussed in the revised manuscript.



Section 4.3 is not directly related to the damage analysis presented and is somewhat speculative. Measurements of the temporal development of snow loads in the Mediterranean region are practically non-existent. I recommend to omit this chapter. Instead, to give further hints on how such rain on snow events can be better managed on a flat roof (slope of roof? arrangement of drainage? emergency outlets?). Further, it would be helpful to indicate what information would be useful for a more complete damage analysis in future (e.g. photos immediately after damage? Snow depth measurements? Snow load measurements? ...).

Section 4.3 will be revised according to the following strategy: our study, because of a number of uncertainties about both the meteorological event and the initial state of the structure, suggests that the failure of the Cevennes Irstea building is a combination of a rather exceptional rain-on-snow hazard in a mediterranean context (which may probably evolve in the future) and several weaknesses of the roof and supporting structures. As such, we think this is important to stress both aspects of the analysis. That is the reason why we will keep the content about snow loads in the Mediterranean region, but we will enrich the section by proposing a list of helpful improvements that can be made in the future to assess those potential exceptional events and their bad consequences. Those include recommendations on the design of important elements of the roof structures (slope angle, drainage system, emergency outlets, etc.) as well on operations (before and after the event) that could help to better monitor the meteorological event and analyze the failure.

Further comments:

Line 42/43: deficient building, better: insufficient material strength?

This proposition will be taken into account in the revised version of the manuscript.

Line 53: Determining the ultimate bearing capacity of a building is similar to or more difficult than determining the possible snow load.

We agree that it is particularly challenging to obtain the ultimate bearing capacity of a building made of a complicated combination of different elements of various shape and size, with some uncertainty on the material properties of each element as well as on the initial overall state of the building due to some previous potential localized defaults of some of the elements. We had already mentioned that this is a delicate question indeed (l.57) but we will further stress this point in the introduction of the revised manuscript.

Line 56: What is the AROME numerical model?

The AROME model is the fine mesh numerical weather forecast model operated by the national weather forecast service in France (l. 74-75). This will be specified in the revised version of the manuscript.

Line 64: What changes are expected about the characteristic snow loads…. not clear what is the meaning.

This sentence is about the evolution in a context of climate change, for example an increase in snowfall, as shown by Croce and Landi (2021). This will be clarified in the revised version.

Lines 79 – 95: Add precipitation data.

Precipitation amounts obtained from the AROME numerical weather model are strongly biased, and can produce very large and unlikely intensities. As a consequence, we do not indicate these precipitation data in this section.

Lines 97: Why is the rain-on-snow event exceptional? Return period of event?

Such a snow event is rare in the region of Montpellier. Ground measurements indicate that snow depth of more than 25 cm have occurred only five times since the 1950s (35 cm in February 1954, 35 cm during the winter 1962-1963, 27 cm on the 14-16/01/1987, 28 cm on the 22/01/1992 and the event described in the present manuscript). The return period of the snow event alone exceeds 10 years (five events in 70 years). What makes the rain-on-snow event exceptional is the large amount of rainfall which has followed the snow event. We do not know if the other large snow events were followed by an intense rainy period. As a consequence, it is difficult to provide a return period for the “rain-on-snow” event.

Fig. 4: add the location of the collapsed structure

See new Figure 4 above.

Line 129: Explain why 30 – 35 cm were chosen (see Fig. 4: 20-30 cm). Give some reference values for new snow density: 250-350 kg/m3 seems to be too high.

In the new Figure 4, we see that the building was located just next to the 30 cm curve. 30 cm is considered as the best estimate, but we consider that there is an uncertainty around this estimate. We now consider an upper bound of 250 kg/m3 for the initial density of the snowpack before the rainy period (see our previous response to one of the reviewer’s comments on this point).

Line 134: The rain on snow event should be discussed in more detail. How much water can the snowpack absorb? What can be the density of a wet snowpack?

The capacity of a snowpack to absorb water really depends on its initial porosity as well as on the boundary conditions of the problem. Very loose snow such as dry and cold fresh snow (50-100 kg/m3) can quickly absorb a lot of water over a few hours, while denser snow (already wet in particular), such as the one probably involved in the event addressed in the present study, may have much more limited capacity to absorb water (Marshall et al. 1999). In the former case, water will follow preferential paths and will start to accumulate in some zones at the bottom. If boundary conditions prevent water evacuation, the resulting snowpack will be very heterogeneous with some zones of soared snow (300 kg/m3) and other zones of accumulated (pure) water at the bottom. In the latter case, water will infiltrate everywhere and settle the snow forming a rather homogeneous wet snowpack. In natural conditions (open system), with constant circulation of water and homogeneous snowpack, we do not expect densities higher than 300-400 kg/m3 over a typical daily period (Marshall et al. 1999, figure 2). If boundary conditions prevent water evacuation (closed system) and depending of the amount of water available (intensity of the rain event until building collapse), we may expect higher values for the ultimate density, which corresponds to an equivalent mean density for the mixture of wet snow (in some zones) and water (in other zones). This point will be further discussed in the revised version of the manuscript. We will discuss in more detail a possible ultimate value for the equivalent density of the mixture of snow and rain just before collapse.

Reference:

H.P. Marshall, H. Conway, L.A. Rasmussen. Snow densification during rain. *Cold Regions Science and Technology* 30, 35-41 (1999).

Fig. 5: How was snowfall measured? Where is the meteo station Lavalette?

The meteo station Lavalette is located inside the site of Irstea. Snowfall is provided here by the SAFRAN reanalysis, and not directly measured from ground measurements. A rain-snow transition limit is derived from available measurements, the vertical profile of temperature, and other available information.

Line 145: (nearly) flat – the slope of the roof is in a rain-on-snow event very decisive. What means nearly? 1°? 3°?

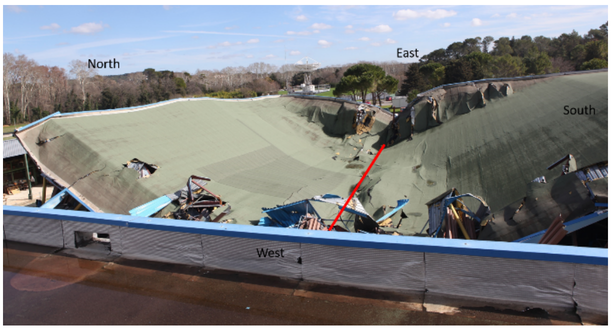
The slope of the roof is equal to 1 %.

Line 154: The drainage system should be explained in detail.

The evacuation of the rainwater will be described in more detail in the revised manuscript (see our previous response to one of the reviewer's comments about this point).

Line 157: central part of the structure: where is that? Indicate the location on a Fig. e.g. 11; The western and eastern facades were "heavily" (not hardly) damaged.

A new figure is proposed on which the part of the roof which totally collapsed is more visible and materialized by the red line on the picture.



Line 161/162: was there an element that was clearly the weakest?

At first glance, on the ground, it was not possible to identify an element that was clearly the weakest. The following question was immediately raised: was the collapse due to the excessive deflection of the lattice structure or to the weakness of some elements? Buckling calculations have then shown that the buckling strength of the rectangular tubes is much lower than that of the other elements. We will include this information and discuss it in the revised version of the manuscript.

Tab. 1: Steel quality of the different structural members?

The table will be completed and it will be explained in the text that the quality of the steel was unknown and was considered as being equal to the one of the S235 quality.

Line 178: "dead" weight

OK , fixed. Thank you.

Line 204: better snow load not snow pressure

OK.

Tab. 3: Better snow load instead of pressure value

OK.

Line 208-209: …by construction the applied pressures. Difficult to understand.

… as pressure (and not snow load) is here the input parameter in the FE modelling.

Line 232: snow load on the ground was estimably 30-35 cm – how was the snow load on the roof? Was a shape factor of 0.8 applied? Was there wind during the snow fall event which reduced the snow height on the roof?

In our study, the snow load on the roof has been estimated to be equal to the snow load on the ground. We think this is a reasonable assumption because of the following reasons: the roof slope was low, a small wall was present all around the edges of the roof, and the wind was not important enough to modify (reduce) the snow height on the roof. The shape factor of 0.8 was only used to back-calculate the snow load recommended by the regulation.

Line 255: difficult to understand: the highest height scenario…

OK, this will be replaced but "In the case of a 35 cm snowfall…".

Line 278: which were the detected structural weaknesses?

The detected structural weaknesses are the east facade, where the biggest stresses and buckling are observed and also the important length of the lattice roof.

Line 285: "a maximum range of span to be on the safe side"…difficult to understand: If the planned geometry of a building is taken into account in the design of the load-bearing structure, a structural failure should not occur. In connection with the drainage, the roof pitch and the sags in the service state would need to be checked.

This is a delicate point. We just want to report here that a similar roof lattice structure was built (nearby building) and did not collapse under the same meteorological event. That's the reason why we mention this fundamental difference between the two buildings with the presence of many inner walls in the intact one. But we do not conclude that this is the reason for the collapse in the end. We will qualify our argument in the revised manuscript.

Line 334: Is there some evidence that the drainage openings were blocked by ice? With temperatures around 6° C might be hardly the case?

The drainage openings, which were only 20 cm high, were certainly not blocked by ice but simply by the dense snowpack already in place when the precipitation turned into rain.