RESPONSE TO REVIEW OF MANUSCRIPT NUMBER: NHESS-2022-93

We thank the editor for giving us the opportunity to submit a revised version of the manuscript. We agree with most of the comments made by the reviewers and we have tried, as much as possible, to integrate them in the revised manuscript. In particular, new simulations have been performed in order to take into account a more accurate geometry of the east facade, the buckling of the structure and its imperfections.

First of all, we want to clarify that a new archival research has allowed us to clarify the distribution of the posts of the eastern facade of the building and their profile, for which we had little information. So, the new simulations performed in order to take into account the comments of the reviewers consider new more realistic features for the eastern facade too.

Reviewer #1 :

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

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 provide a revised version of our manuscript which (i) better explains 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 but are not available) and (ii) provides 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 provide some additional analysis, thanks to analytical buckling calculations which 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 was not closely related to this study and we have followed this recommendation. We have removed the first paragraph and started 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 March 1 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 at 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 has been modified and shows now 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 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 towards the edges of the roof and in the other case we assumed that water mainly accumulated in the center of the roof. In Sections 3.2 and 3.3, we present and discuss the consequences of those different scenarios, respectively.

- 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 11 and in an overview sketch inserted in Figure A2.

- Were there any eyewitnesses?

The entire site was evacuated in the early afternoon of March 1; only the caretaker was present 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 is indeed a spatial supporting structure which extends over the entire roof surface and withstands all the forces acting upon it.

- 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 each side of the peak line oriented north south. This is now indicated at line 182.

- 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. There were four outlets at the end of the north and south edges, one in the middle of the west edge, and two at quarter and three-quarter of the east edge, as indicated now by the red arrows in Figure 6. All this information about the water drainage system has been added to the revised manuscript.

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

The Irstea Cévennes building dating back to 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. The type of steel used for the supporting structure is therefore unknown, and we recall here that no material testing was carried out after the collapse. We therefore assumed that the supporting structure was made entirely of the S235 steel, which is 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 January 14-16, 1987;

- Around 28 cm on the January 22, 1992;

- Less than 10 cm on March 7, 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 the same day at the station of Montpellier from Météo-France, and does not seem to be corroborated by other sources, we have changed 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.

Figure 4 in the revised manuscript indicates 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 is 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. They do indeed demonstrate that a local buckling of tubular crossbars in lattice roof occurs for lower snow loads compared to other failure criteria.

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, three different cases of loadings (see figure 13) for a snowfall height of 30 cm are now studied. The results corresponding to those different scenarios are now 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? ...).

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 made the decision to keep the content about snow loads in the Mediterranean region.

In section 4.2, we now insist on the need to encourage greater attention to the design of large span roofs, in the context of climate change leading to an increase in the frequency and intensity of snow events. Moreover, we conclude that it would be interesting to conduct research on the effectiveness of various drainage systems under snowy roof conditions, and to provide recommendations regarding the required roof slopes and on the selection and design of downstream evacuation devices.

However, it seems difficult for us to suggest taking photos or measurements during the crisis period that could add an additional risk, given that the priority in this case should be to save human lives.

Further comments:

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

This proposition has been 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.58). In the revised version of the manuscript, both aspects have been switched to avoid implying that the second question holds more significance than the first, even if the second issue is addressed first in the rest of the article.

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 is now 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 is now 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 that has followed the snow event. We do not know if the other large snow events were followed by an intense rainy period. As such, 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.

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 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 is now further discussed in the revised version of the manuscript. We 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 %. This is now indicated in the revised manuscript.

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

The evacuation of the rainwater is described in more detail in the revised manuscript (Section 3.1.1).

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 (Figure 10) has been introduced, in order to highlight the portion of the roof that has completely collapsed, which is indicated by the red line on the picture.

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

On initial inspection from ground level, it was difficult to identify any particular element that appeared weaker than others. This led to the question of whether the collapse was caused by excessive deflection of the lattice structure or weakness in some individual components. Buckling calculations were subsequently conducted and showed that local buckling (of tubular crossbars) can occur and was a possible cause of the collapse. We have included this information and discussed it in the revised version of the manuscript.

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

It is now 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…

This sentence has been removed from the revised manuscript.

Line 278: which were the detected structural weaknesses?

The detected structural weaknesses include the tubular crossbars, where buckling has been observed, as well as the significant 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. Our report aims to highlight that a nearby building, which had a similar roof lattice structure, did not collapse under the same meteorological event. We mention the presence of many inner walls in the intact building, which is a fundamental difference between the two structures. However, we do not conclude that this is the reason for the collapse of the other building. We have revised the manuscript to clarify this point and emphasize the importance of properly designing near-flat roofs in a context of possible increased snow-and-rain loads.

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.

Reviewer #2 :

RC2#1 The topic of the manuscript is appropriate for the Journal, but due to a number of deficiencies the manuscript cannot be recommended for publication. The reviewer recommends REJECTING based mainly on the following arguments:

A) The analysis is at some steps too simplified and many important aspects are not analysed.

B) In general, the manuscript raises more questions than it provides answers. Based on the arguments below, the conclusions of the study seem to be poorly grounded. The authors fail to adequately support their conclusion "*The collapse of the Irstea Cévennes building can certainly be explained by the intensity of the rain-on-snow event, and by the fact that the water could not flow, as the drainage system was blocked by frozen snow settled at the bottom under cold conditions*." What was wrong then? Structural design? Low design loads in the standard? It is insufficient to claim that a wrong drainage system was the only cause. Can we substantiate that there was free water able to flow on the nearly flat roof at the time of collapse?

C) The manuscript is structured in a way that is difficult to follow – the main text often refers to the annexes where little information is provided then.

We thank the reviewer for these comments. Please see below a detailed response to each of these comments and the proposed modifications.

RC2#2 "*In our study, it is supposed that the initial state was perfect and corresponded to all the features provided in the previous subsection*." From a perspective of forensic engineering, this assumption is very doubtful. We have evidence that the structure collapsed and a similar neighbouring structure survived, and by experience we know that a vast majority of collapses was caused by gross errors. And yet we still consider the state of the structure before the collapse was perfect? Assuming the perfect initial state, the analysis of the second structure may reveal similar load bearing capacity as for the collapsed one.

When we stated that the initial state was supposed to be perfect, we meant that this study was conducted without considering any prior deterioration of the structure due to temporary loads that may have been applied during past events, as we have limited information on them. To our knowledge, the heaviest snow loads that the building had to bear since its construction were:

- around 27 cm on January 14-16, 1987;
- around 28 cm on the January 22, 1992;
- less than 10 cm on March 7, 2010.

Although these snow loads could cause buckling, we do not have information on any possible damage that the structure may have sustained in the past.

Concerning the neighbouring building, it has a main metal frame similar to that of the structure we studied, but it also has several load-bearing walls inside due to the presence of multiple house offices. This prevents significant bending of the metal frame, which may be one reason among others why this neighbouring structure is stronger and was able to withstand the rain-on-snow event of 2018 (see lines 281-285 of the original manuscript).

Finally, we conducted a buckling analysis that considers imperfections.

RC2#3 Did past surveys of the structure report any defects? Corrosion? Deflections and imperfections? How about the second building – is there any evidence of imperfections, deflections? This could be relevant, assuming the structures were built in a similar way.

To our knowledge, no survey has been conducted on the structure of the Cévennes and Minéa buildings between the date of their construction date and the 2018 incident. Following this event, only a technical opinion of the strength of the adjacent Minéa building was requested. This report concluded that the overall strength of the structure was satisfactory, but a number of points requiring vigilance were identified:

- significant stagnation of stormwater on the roof;

- slight buckling and traces of corrosion on some profiles (angles and tubular profiles) at the level of the roof metal frame;

- buckling on one of the profiles of a Saint-Andre's cross;

- V-columns in satisfactory condition, with slight corrosion at the head and anchor plate;

- cracks and chips with visible reinforcements in concrete blocks used for anchoring V-columns.

This information about the overall state of the neighbouring building after the 2018 event, as well as a brief discussion on this information, have been added in the revised manuscript (Sections 3.3 and 4.2.).

RC2#4 Is there any evidence that the drainage system was blocked and water pooled on the roof? Was the snowpack frozen / icy due to previous freeze-thaw cycles or was it already melting? Analysis of air temperatures a few days before the collapse could help.

Photographs taken a few days after the rain-on-snow event of 2018 clearly show a stagnation of water on the roof of the neighbouring building and therefore a problem of stormwater drainage, as mentioned among the points of vigilance identified in this building (see our response to the previous comment). This strongly suggests a similar problem for the Cevennes building before its full collapse.
The drainage openings, which were only 20 cm high, were certainly not blocked by ice (the temperature being between 0 and 4°C on the day of the collapse) but simply by the dense snowpack already in place when the precipitation turned into rain. As indicated in Section 2.1, this meteorological event followed a cold spell and air temperatures were largely below 0°C when snow started to fall (see Fig. 5): the snowfall event only occurred on the 28th of Feb. 2018 and there was no snowpack before this date. Moreover, all testimonies indicate a wet snowpack at the end of the snowfall.
We improve our discussion on the above-mentioned points in the revised manuscript.

RC2#5 Many details of the structural analysis are missing; some assumptions need thorough revision:

The authors try to make a retrospective analysis of "what likely happened before the collapse". While correctly considering best estimates of the roof snow load, they fail to consider best estimates for material properties – according to the new Eurocode for design of steel structures, prEN 1993-1-1:2022, S235 has mean of $f_y = 1,25 \times 235 = 294$ MPa, mean of $f_u = 1,2 \times 360 = 432$ MPa, $\varepsilon_u \geq 15\%$. In prEN 1993, 235 MPa is said to correspond to a 1‰ fractile of the distribution of fy, thus a very low – very conservative – very unlikely value. Consideration of more realistic values for material properties would likely amplify the importance of failure modes related to loss of stability.

We took pessimistic values for material properties to somewhat offset the fact that we supposed a perfect initial state of the building. We thank the reviewer for those information about material properties and ran new simulations with $f_y = 294$ MPa, $f_u = 432$ MPa and $\varepsilon_u=20\%$. The results of the new simulations based on the assumptions proposed by the reviewer are now presented in the revised manuscript.

RC2#6 Loss of stability will contribute to collapse mechanisms of common steel structural members. Expected values of eccentricities and imperfections should be considered in the analysis. How was this done?

There are already a number of sources of uncertainty regarding the initial state of the structure (e.g. material properties, as for instance discussed in the previous comment) and the intensity of the climatic event (snow height and density, amount of rain, etc.). For simplicity, no eccentricities or imperfections were taken into account in our previous analysis.
However, we agree that global and local structural imperfections should be taken into account in the analysis. So, new simulations have been performed to analyze buckling taking into account imperfections as a linear superposition of buckling eigenmodes. This analysis is presented in the revised manuscript.

RC2#7 *ultimate limit criterion (full failure and collapse of the structure)*. When considering εu ≥ 15%, exceeded fu in one cross-section is unlikely to lead to collapse, right?

In fact, yield and ultimate criteria mentioned in the article are satisfied when an accumulation of stresses equal to the yield and ultimate strengths of steel in a part of the elastic or elasto-plastic model leads to the code divergence. This point has been clarified in the revised article.

RC2#8 *We also conclude that the building, at the moment of its collapse in 2018, was respecting the new regulations*. How is this substantiated? Assuming it was in the perfect initial state before the collapse?

Due to new simulations that take into account the more accurate geometry of the east façade, as well as the buckling of the structure and imperfections, the conclusions of the analysis regarding the collapse of the building, considering the regulations, have now changed.

RC2#9 *Under current regulations, yield occurs for a load less than the exceptional load recommended by Eurocode but the building fails serviceability (excessive deflection) for snow load largely above the permanent project situation and slightly above the accidental project situation recommended by Eurocode*. Numbers are missing here.

The values of loads leading to yield and excessive deflection were provided in Table 3 of the original manuscript, whereas the loads corresponding to the characteristic and exceptional project situations (0.8 * 550 + 200 = 640 and 0.8 * 1 350 + 200 = 1 280 N.m-2, respectively) were provided in lines 389-390. We agree that those values should be reminded in the paragraph mentioned above for a better readability. So, in the revised paper, we detail (as mentioned above) the values of loads corresponding to the characteristic and exceptional project situations in lines 516-522 and we modify the paragraph mentioned by the reviewer integrating values.

RC2#10 Details of the roof snow load modelling are also missing:
This rain-on-snow event is exceptional – this should be quantified – what is an occurrence rate of such an event? Snow load maxima (including the effect of rain on snow) should be analysed for the location and the return period for the ground snow load experienced at the event should be estimated. This would help to classify if the ground snow load reached serviceability, design (return period of ~hundred years) or accidental load levels. Missing are details for the roof snow load – what is the characteristic roof load? What is the design value? How do they compare to the estimated roof load?

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 of 2018 described in the present manuscript. The empirical return period of the snow event alone exceeds 10 years (5 events in 70 years). What makes the rain-on-snow event exceptional is the large amount of rainfall that has followed the snow event. We do not know if the other large snow events were followed by an intense rainy period. Moreover, it is difficult to apply a standard statistical approach (using the fitting of a probability distribution) to snow load maxima at this location (i) because of the absence of systematic measurements and (ii) because of the vast majority of zero values in the series of annual maxima, snow events being very rare in this Mediterranean region (Section 4.3). As such, it is not possible to provide a precise return period for the "rain-on-snow" event.

Regarding the second part of the comment, the roof snow load was assumed to be equal to the ground snow load. For the 2018 rain-on-snow event, this load was estimated between 735 and 860 N/m2 before rain for a snow density equal to 250 kg.m-3 and a snow height of 30 cm and 35 cm, respectively. After the rain, the load was estimated to be between 1 765 and 2 060 N/m2 for a snow density equal to 600 kg.m-3. The load leading to the failure of the structure obtained by the FE simulations (red lines) is compared to those values (blue markers and lines) in Figure 17.

RC2#11 … *we can roughly estimate that the very wet snowpack on the roof easily reached a high density around 600 kg.m−3 at the time of the collapse*. In the scientific paper such estimates should be based on sound arguments.

The assumed value of 600 kg/m3 for ultimate snow density was deemed to correspond to an "equivalent" snow and rain density uniformly distributed over the roof. In fact, the wet snowpack was probably heterogeneous with areas of soared snow at higher densities (300-400 kg/m3) than the initial (already wet) snow (250 kg/m3) and other areas at the bottom with accumulated water (1000 kg/m3) due to preferential water flows. The value of 600 kg/m3 corresponds to an equivalent value used to define the (equivalent) pressure exerted by the combination of snow and rain accumulations. Following remarks by the first reviewer, we now account for the heterogeneity of the mixture of wet snow and water, by considering different scenarios of (simplified) non-uniform pressure distributions that are presented in the revised version of our manuscript (more details about those scenarios for pressure distributions are given in our reply to reviewer #1).

RC2#12 How was the effect of exposure considered? What was the wind speed during the snowfall? For many flat roofs, it holds roof snow load = 0,8 x ground snow load. Discuss this.

On the day of the collapse, the wind was at force 1, with a velocity between 0 and 4 m/s. It is therefore unlikely that the wind could have had an effect on the snow distribution on the roof before and at the time of the collapse. 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, the snow was wet and relatively heavy and the wind was not strong 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 (see our response to the comment RC2#9).

RC2#13 How important are wind effects for the design of structural members? Is wind negligible in comparison to snow?

Extreme wind conditions must be considered when designing structural members, as stated in Eurocode 1. However, wind effects were negligible on the day of the collapse. Therefore, we did not assess this aspect for the 2018 event, as it falls outside the scope of our investigation.

RC2#13 The first paragraph of the introduction is very general – it seems to have no link with the other text. Delete it or make clear how it is related to the following analysis.

We agree that this first paragraph was not closely related to this study. As a result, we have removed it and begin now the introduction by focusing on static snow loads.

Editorial comments:

- Terminology: this type of roof is commonly referred to as “flat roof”, not a plate roof.
- The use of English could be improved. In particular damage should not be (in the context of this study) used in plural.
- The check by a native speaker experienced with technical texts would help to re-phrase some clumsy statements.
- Some typos appear in the text. Lineic is line load?

We thank the reviewer for providing language corrections. We have incorporated these corrections in the revised version of the article.

Reviewer #3:

The paper investigates the collapse of a steel building, built in 1982 in Montpellier in the south of France, under snow and rain loads occurred in 2018, providing detailed information of the meteorological event, its features, influence on snow accumulation on the building as well as on the subsequent rain event, heavily affecting the snow density and the resulting load acting on the roof.

The paper continues with the FE modelling of the structure, to simulate the collapse condition trying to estimate, by means of back analysis, the actual load intensity which led to the collapse.

On the following parts clarifications are needed.

RC3#1. In Annex C it is stated that the structure is not known in detail and some simplifications and assumptions on the real geometry are introduced in the FE model, the influence of which in the results is also checked by means of a "virtual". This kind of assumptions may significantly affect the validity of the FE results and more explanations are needed. In particular, a detailed list of missing information should be added, commenting on the potential impact of the induced uncertainty in the FE model. Some drawings showing the structure and its elements (cross sections, dimensions, etc.), possibly from the time of the construction, could help in better understanding the structural behaviour.

The elevation plans of the building that were retrieved from the archives do not explicitly depict the structure of the eastern façade, which is covered by cladding. Only the sections of the columns surrounding the doors have been provided, and these are the sections that have been used for all the columns of the eastern façade in the FE model. However, following this comment and the feedback of other reviewers, we searched for new information regarding the geometry of the structure and eventually discovered a top view of the building that provides the characteristics of the supporting columns of the eastern facade. It was revealed that the columns are HEA 160 profiles. New simulations have been conducted that take into account this information. As a result, we have (i) incorporated these new data and outcomes in the revised version of the manuscript, which includes more detailed information on the dimensions and sections of the eastern facade elements, and (ii) removed Annex C about the virtual model of the structure, which is now significantly less relevant.

RC3#2. Steel properties are reported in Table 1, clearly referring to nominal values for S235 steel. In a static non-linear analysis, the actual mechanical properties of steel play a fundamental role in the determination of ultimate loads leading to the structural collapse. A clarification on this aspect should be introduced, possibly referring to test results on specimens extracted from the steel members after the collapse or, at least, by making reference to mean values of resistances instead of characteristic values, as it is the case in Table 1.

Unfortunately, no tests have been carried out on steel elements after collapse. This is why the steel characteristic values were used in the FE model. We agree that these values, chosen to (somewhat) balance the fact that the initial state of the structure is considered perfect in the FE model, are pessimistic. As suggested by the reviewers, we performed new simulations that take into account the mean values of the steel strengths according to the new Eurocode for design of steel structures: $f_y = 1.25 \times 235 = 294$ MPa and $f_u = 1.2 \times 360 = 432$ MPa and an ultimate strain $\varepsilon_u = 20\%$. The results of the new simulations are presented and discussed in the revised version of the manuscript.

RC3#3. The mesh sensitivity study, mentioned in line 170-175 and illustrated in Annex A, does not seem appropriate for a truss system, with hinged beams.

As mentioned in lines 188-189 of the original manuscript, the roof frame elements are not hinged. This point is further emphasized in the revised version of the manuscript. Finally, the mesh sensitivity study has been removed.

RC3#4. Collapse criteria illustrated in 3.3 (lines 195-203) are not clear, as it could be interpreted that the collapse is reached as soon as one steel beam yields or reaches the ultimate strength (which is then not expected to occur as this happens only after yielding). In pushover analyses the final collapse mechanism is identified under non-linear static analysis under increasing loads, which is not evident in methodology illustrated in the paper. A clarification is needed.

Collapse criteria as referred in the manuscript are in fact satisfied when an accumulation of stresses equal to the yield and ultimate strengths of steel in a part of the elastic or elasto-plastic model leads to the divergence of the code.

RC3#5. Among the collapse criteria no mention is made on buckling of compressed members, which as expected and as confirmed by the photos of the collapsed structure, has occurred. Buckling anticipates the failure of members with respect to the uniform compression till yielding and this aspect could lead to a significant reduction of the ultimate load in the FE analysis. A clarification is needed.

We thank the reviewer for this comment. The collapsed structure in the pictures appears to have compressed elements that underwent buckling. Although this buckling may not be the direct cause of the rupture and could have occurred during the collapse, it is crucial to provide an analysis of this failure mode. Therefore, a two-step buckling analysis was conducted. Firstly, a linear buckling analysis was performed to obtain the first buckling mode shapes of the structure and the corresponding eigenvalue buckling loads. Next, a non-linear buckling analysis was conducted, which integrate geometric imperfections that correspond to the displacement results of the pre-buckling analysis. The outcomes of this analysis have been incorporated in the revised manuscript.

RC3#6. Considering the flexibility of the structural system of the roof, the assumption of the uniform distribution of the snow load, and moreover of the rain load, all over the roof surface is a strong assumption, which could lead to wrong unconservative results. This aspect is only mentioned as a limitation of the analysis, but should be better illustrated as ponding effects could have caused a significant redistribution of the load, with concentration in the centre of the roof area, i.e. where its effects are more onerous for the system.

We remind here that the roof is not particularly flexible as its frame elements are either welded or bolted together. However, we agree that the assumed uniform load distribution for the total load may be too simplistic. As mentioned in our response to reviewer 1, who also pointed out this point, we believe that the initial snow load was distributed almost uniformly due to the low slope of the roof (1% slope on each side of the peak line of the roof oriented north-south) and the very little wind during the snowfall. Then, rain likely accumulated first on the west and east edges of the roof until the direction of the roof slope changed due to the increase of deflection. Subsequently, the rain accumulated in the center of the roof. Instead of considering only one scenario of uniform distribution for the total load, we are now studying three different cases of pressure distribution, as shown in the figure 13 of the revised paper.

RC3#7. Based on the above comments the discussion of the FE results in 4.4 may need to be reconsidered.

As the eastern facade of the FE model and the steel behaviour law were updated and a collapse criterion on buckling has been added, the discussion of the FE results is carefully reconsidered in the revised manuscript

RC3#8. Paragraph 4.2. It is claimed that the structure respected the structural design codes at the time of the construction as well as at the time of the collapse (2018). Later on in the Appendix it is stated that the SLS limit states were not verified. The particular structural scheme, a steel 3D truss plate with no intermediate supports, is particularly prone to deformation effects, which generally end up in governing the design. Some more details on these aspects are needed, to better understand the validity of the drawn conclusions about the compliance with the design standards.

We agree that the conclusions regarding the structure’s compliance with design standards were unclear. In fact, the structure was deemed to respect the structural design codes at the time of its construction but not at the time of the collapse. In the revised paper, we have provided a more qualified and explicit conclusion about the structure's compliance with design standards, which takes into account the new simulation results.

RC3#9. Line 315: recent climate models provide also snow variables, such as snow depth or SWE.

We are aware of convection-permitting climate models which are able to simulate high-resolution meteorological variables, including snow variables such as snow depth or SWE (https://doi.org/10.1002/joc.7637). However, to our knowledge, these simulations are not available in the south of France where snow events are rare. These simulations have been obtained in priority in high-latitude or mountainous regions (e.g. the pan-alpine region).

RC3#10. In the conclusions it should be better highlighted which are the main outcomes of the study, i.e. which sort of recommendations are proposed by the Authors also in view of the revision of structural design standard or for the analysis of existing buildings.

We thank the reviewer for this suggestion, and we incorporated it by summarizing the main findings and recommendations in the concluding section of the revised manuscript.