Response to Comments CC2

Comment:

The paper aims at exploring gaps around the robustness of bridges to the flood hazard on the basis of an expert workshop that took place in April 2021 with the participation of academics, consultants and decision makers operating in the United Kingdom. The topic is urgent and timely.
I understand that the paper sections are stated to be derived from a "workshop and subsequent meetings". However, the "workshop dimension" cannot be seen in the paper. For example, I was expecting to be told how the workshop was run and which information was sought (and how), how the participants were chosen and which expertise they were bringing to the table. The obvious reference here is Lamb et al. (2017) (https://nhess.copernicus.org/articles/17/1393/2017/nhess-17-1393-2017.pdf)/ . The paper reads more as an interesting review, since it does miss to link the outputs, techniques and discussion of the workshop to what is presented in the paper. It is not evidenced how Table 1 was obtained through the workshop and co-working, to give another example. Perhaps, it is worth to consider re-framing the paper within a "review" structure/perspective – or to report how to workshop was structured and how the paper's information was obtained.
Finally, the paper would have benefitted by discussing topics that were left out of the workshop (and could act as "future research"), such as netzero.
Minor comments below.

Reply: We thank the Reviewer for her comments and insights, which contributed improved the quality and clarity manuscript.

The workshop was run online during Covid restrictions. The academics from the University of Strathclyde, Surrey and Southampton that authored the manuscript invited their contacts and collaborators from the industry and transport agencies to attend the event. The main purpose of the event was for the academics to disseminate their latest research developments to the industrial partners, and to discuss about the existing knowledge and capability gaps in academia and industry with the aim of scoping a research agenda. Thus, the scope of the workshop was very different from that of Lamb et al. (2017), who focused on the uncertainties about the vulnerability of bridges to scour.

During the event, the partners introduced themselves and shared their experience, highlighting what were in their opinion their most challenging and urgent research needs.

It is noteworthy that not all the partners could attend the first workshop, and for this reason, some follow-up meetings were organised with some of the co-author of this study. The meetings and workshops were complemented by several exchanges of emails, where some partners shared additional thoughts and insights.
An online Word document was then created by Enrico Tubaldi, who also prepared a first draft of the manuscript with an initial structure. Each coauthor was given access to it and contributed to it. The manuscript underwent several revisions, until the final submission, which was approved by all the coauthors.

The section entitled "Author contributions" at the bottom of the manuscript highlights the contribution of the various co-authors to the document.
"*All authors participated to the workshop or subsequent meetings underpinning this invited perspective. Enrico Tubaldi wrote the manuscript with contributions from all co-authors. Significant contribution was given by Gustavo de Almeida on section 2.1, Alonso Pizarro on section 2.2, Rob Lamb on section 2.3, Stergios Mitoulis on section 2.4, Eftychia Koursari on section 2.5, Christopher White and Jim Brown on section 2.6, Richard Mathews on sections 2.2, 2.3 and 2.6. All the coauthors reviewed the paper and provided additional perspectives that enhanced the final version.*"

The authors believe providing additional information in the manuscript about how the workshop was run and further information exchanged would distract readers from the main goal of the manuscript, which is to highlight knowledge gaps, and cast the directions for future research and actions by academics, practitioners and bridge managers to improve bridge resilience to flooding. However, the response to this very interesting point raised by the Reviewer will be shared together with the document and could be accessed by the interested readers.

Regarding the choice of the format of the paper (i.e., Invited Perspectives article), our aim was not to provide a comprehensive state-of-the-art review of the problem, but to share "new ideas, views, or perceptions on a topical aspect of natural hazards", and "to stimulate an open debate among peers via the discussion phase", as per the guidance:

https://www.natural-hazards-and-earth-system-sciences.net/about/manuscript_types.html

Thus, following a consultation with the journal Editors, we decided that the manuscript would fall into the category of "Invited Perspectives" rather than "Review articles".

We also agree with the Reviewer that "netzero" is a very timely and important topic, and that it could have some links to bridge resilience. For example, extending bridges' design lifetime can contribute to netzero goals. However, this topic has not emerged during any workshop and subsequent meeting and thus we would prefer not to mention it in the paper.

Comment:
L47: "to be of the order of 160,000 in total with the Highways Agency …" may need rephrasing
Reply: The original sentence

".., but the number of bridges is estimated to be of the order of 160,000 in total with the Highways Agency (Middleton 2004), with about 30,000 of these crossing waterways"

has been rewritten as follows:

"The number of bridges managed by the Highways Agency is estimated to be as high as 160,000, with approximately 30,000 of these crossing waterways (Middleton 2004)."

Comment:
L47-50: what about all the other (non HA- or NR-owned) bridges?
Reply:
We don't have this figure, but we have provided additional information regarding road bridges managed by councils across Great Britain:
The estimated cost to retrofit the 3,105 bridges managed by local councils classified as "substandard" is approximately £1 Billion (£985 million). However, budget restrictions mean that only 392 of these substandard bridges will likely have the necessary work carried out on them within the next five years (RAC Foundation 2021).

Comment:
L64: used "£" for pounds before
Reply:
Corrected, thank you.

Comment:
L66: "this" what?
Reply:

We have rewritten the sentence as follows:

" The projected increase in winter precipitation and river flows due to climate change is expected to increase further the risk of bridge failure due to flooding (Jaroszweski et al., 2021). This issue is also exacerbated by.."

Comment:
L75: "the" Univ of Strathclyde (and also "the" for Surrey's and Southampton's)
Reply:
Thanks, we have added the "the" before "University".

Comment:
L133: used "and" instead of & before and after
Reply:
We apologise but did not understand this.

Comment:
L13: used "formulae" instead of formulas before
Reply:
Thank you for pointing this out, in the revised version of the manuscript we use only the term "formulae".

Comment:
L144, 243, 344, 431, 482, 493: "this" what?
Reply: We checked the use of this and believe there is no problem with it.

Comment:
L318: authors may want to refer to the updated version of BD97/12
Reply:
CS 469 has not been published yet. However, following the Reviewer's recommendation, we have added the following reference:
Takano, H., Pooley, M. (2021). New UK guidance on hydraulic actions on highway structures and bridges. *Proceedings of the Institution of Civil Engineers – Bridge Engineering*, 174(3): 231–238, https://doi.org/10.1680/jbren.20.00024.

Comment:

L460-3: how can "Satellite imagery, aerial photography and UAVs technology (Figure 5) can also be very useful…"?

Reply:

Morphological changes in rivers can led to aggradation, degradation, or lateral migration of the stream channel, all of which affect bridge scour. See e.g.

Brice, J. C. (1984). Assessment of channel stability at bridge sites. *Transportation Research Record*, (950).

Lagasse, P. F., Zevenbergen, L. W., Spitz, W., & Arneson, L. A. (2012). *Stream stability at highway structures* (No. FHWA-HIF-12-004). United States. Federal Highway Administration. Office of Bridge Technology.

The second reference has been added to the manuscript.

Comment:

L487-489: I think Digital twins are just an example of technology for this paper, rather than a conclusion of it (since there is no evidence before leading to it in this section).

Reply:

The sentence in the original manuscript:

"*This can help shift the flood risk assessment paradigm from manual and inaccurate diagnoses that rely heavily on costly and potentially inaccurate visual inspections, towards impact-based forecasting and near real-time evaluations of the risk supported by digital twinning technologies (Ye et al. 2019). It can also help to better define strategies to tackle the uncertain effects of climate change and socio-economic growth.*"

has been rewritten as follows:

The results of the actions described in Table 1 can help shift the flood risk assessment paradigm from manual and inaccurate diagnoses that rely heavily on costly and potentially inaccurate visual inspections, towards impact-based forecasting and near real-time evaluations of the risk supported by sensor technologies. This would ultimately help to accelerate the development of SHM-based digital twin platforms (Ye et al. 2019) for the management of bridges at risk of flooding, which are currently missing. It can also help to better define strategies to tackle the uncertain effects of climate change on the risk of bridge failure due to floods.

The revised Table 1 is attached at the end of this document.

Comment:

Table 1: what about the lack of flood damage models/curves for bridges at risk of flooding. What about resilience or restoration models? If these topics did not come out during the workshop, perhaps discuss anything that was left out during the event but worth to be mentioned? Also, maybe "data integration" rather than fusion?

Reply:

We agree with the Reviewers that there is a lack of flood damage models/curves for bridges at risk of flooding, as pointed out in Section "2.3. Vulnerability of various bridge typologies".

The actions we recommended in order to fill this knowledge gap are already in Table 1:

- Identification of optimal intensity measures to be used in fragility analyses for describing the joint effect of various flood actions on bridges.
- Definition of methodologies for evaluating the vulnerability of various bridge types to concurrent flood-induced actions, accounting for cumulative effects (e.g. scour accumulated in previous floods) and the effects of debris through advanced modelling of water-soil-bridge assets.

Regarding the problem of restoration models, this topic was not addressed in depth during the workshop. Stergios Mitoulis mentioned to the attendees his elicitation study, and it was established that recovery models for bridges affected by floods are generally missing. This leads to the absence of quantitative resilience models for various bridge types. The problem is discussed in the following references:

Mitoulis, S. A., Argyroudis, S. A., Loli, M., & Imam, B. (2021). Restoration models for quantifying flood resilience of bridges. *Engineering Structures*, *238*, 112180.

Mitoulis, S. A., & Argyroudis, S. A. (2021). Restoration models of flood resilient bridges: Survey data. *Data in brief, 36, 107088.*

The following item has been added in Table 1.

Resilience quantification	- Restoration models for different types of bridges and different operators (masonry arch bridges vs. multi-span concrete bridges, road or railway bridges). - Life-cycle resilience metrics for multiple flood scenarios including climate projections	(4),(5),(6),(7)

The term and concept of "data fusion" is well established in the context of Structural Health Monitoring, see e.g.
https://en.wikipedia.org/wiki/Data_fusion

Thus, we would prefer to keep this term.

Table 1. List of research challenges, needs and actions for improving bridge resilience to flooding.

Area	**Research challenges and needs**	**Actions**
Hazard assessment and mitigation	- Characterization of the likelihood of accumulation of debris at bridge piers. - Critical review and evaluation of the effectiveness of technical solutions for mitigating hydrodynamic forces for bridges at risk of inundation. - Extension of current flood forecast and warning capabilities to longer lead times and uncertainty characterization. - More accurate modelling of the impact of climate change on frequency and intensity of flooding.	(1)-(5)
Hydraulic actions modelling	- Additional field research, data collection and analyses also needed to characterize the interrelated flood actions and validate models. - Characterization of the temporal evolution of scour under the influence of time-varying intervening variables characteristic of flow and debris, with further experiments extending the range of applicability of developed approaches. - Characterization of the effect of bridge pier and foundation geometries on the development of scour and on the scour hole shape. -Development of models for establishing the relationships between measured river parameters (flow height, surface water velocity) and parameters controlling scour and hydraulic actions (e.g. depth averaged velocity).	(1)-(5)
Vulnerability assessment and reduction	- Identification of optimal intensity measures to be used in fragility analyses for describing the joint effect of various flood actions on bridges. - Definition of methodologies for evaluating the vulnerability of various bridge types to concurrent flood-induced actions, accounting for cumulative effects (e.g. scour accumulated in previous floods) and the effects of debris through advanced modelling of water-soil-bridge assets. - Statistics of the principal causes of failure and collapse mechanisms for various bridge typologies. - Cost-benefit analysis of alternative solutions for mitigating the risk of different bridge components (e.g. deck unseating and uplift).	(1)-(6)

Risk management	- Development of decision support tools to aid bridge managers to identify optimal actions for emergency/long-term flood risk management (including restoration and/or adaptation measures to climate change). These should take into account the bridge fragility and the consequences of bridge failure. - Identification of actions that could be taken in the short term to mitigate the impact of forecasted floods (e.g. removal of debris accumulated at piers). - More explicit considerations of structural vulnerability indicators and consequences in risk rating procedures. - Improvement of response and recovery procedures that are kept up to date with the most recent technologies.	(2),(4)-(8)
Impact-based forecasting	- Tools enabling the paradigm shift from flood hydrograph to impact-based forecasting, so that mitigation measures can be better planned and justified using cost-benefit criteria. This could contribute to an increased awareness of the actual risk of bridges and a better acceptance of mitigation measures by affected communities.	(2)-(5)
Monitoring	- Evaluation of the metrological effectiveness of sensors for monitoring the effects of floods on structures. - Development of approaches for fusing information from numerical models and heterogeneous sensing systems, providing observations and measurements of different parameters involved in the risk assessment. These approaches should consider the uncertainty inherent to the models and the observations, which can be of different nature. They should also be able to propagate these uncertainties through the various steps contributing to the risk evaluation. - Incorporation of monitoring technologies into risk management procedures.	(2)-(8)
Value of information of data	- Quantification of the benefits, in terms of cost savings to bridge operators and ultimately to communities, of data and information from sensors. This requires the development of a methodology for comparing the value of information from systems characterized by different measured quantities, accuracy, and spatiotemporal resolution. This effort could help to increase the adoption of sensors for monitoring bridges and rivers by bridge managers and operators. - Cost-benefit analysis of risk mitigation measures (rip-rap) vis-a-vis bathymetric surveys and accurate foundation depth evaluations for identifying the most effective scour management strategies in case of unknown foundation depths.	(2)-(8)
Resilience quantification	- Restoration models for different types of bridges and different operators (masonry arch bridges vs. multi-span concrete bridges, road or railway bridges). - Life-cycle resilience assessments considering multiple flood scenarios under climate change effects.	(4),(5),(6),(7)

Actions: (1) Laboratory and in-field experiments; (2) Development of models and techniques; (3) Numerical analyses; (4) Pilot case studies; (5) Data gathering (trough monitoring or desk studies); (6) Academic-industry workshops and engagement events; (7) Engagement with general public; (8) Training of experts, inspectors, recovery teams.