ASSESSMENT OF DAMAGED ARCHES

J. A. Martín-Caro, D. López

INES Consultant Engineers, Madrid, SPAIN.

e-mails: jmc@inesingenieros.com, dlo@inesingenieros.com

SUMMARY

The present paper presents a description of an assessment procedure developed for damaged masonry arch bridges. The following pages focus in justifying why the presence of certain damages requires an extra analysis based on the service behaviour of these structures. The overall purpose is to call the attention of the railway administrations and of the technicians about the existence of certain type of damages, which structural impact is not entirely known and therefore need to be studied in order to avoid the normalization of uncertainties, which is currently prevailing.

Keywords: *Masonry arch bridges, UIC, damage classification, damaged structures, service loading conditions, 3D behaviour, control variables, critical values.*

1. INTRODUCTION

This work forms part of the UIC project P/0314. Assessment of masonry arch bridges, carried out during 2012-2015. It is part of an overall strategy of having a better understanding of the behavior of these structures under service loading conditions and having in consideration the existing damages.

The purpose of this study is twofold, on one hand define a damage classification according to their impact on the bridge behavior, and on the other hand, intend giving advice on how to represent and take in consideration these damages, so that it can be studied how the structural behavior of these bridges is affected by them.

2. PRELIMINARY ASSESSMENT – DAMAGE CLASSIFICATION

The carried out damage classification is based in a previous wok undertaken by UIC members, which consisted in collecting those damages that could be visually identified in this type of bridges. The information of over 2000 bridges from 8 different countries was put together in a document called Catalogue of Damage [4]. Such catalogue already undertakes a first damage classification based on the elements where they appear and differentiates between damages with a durability origin and due to a bad strength behavior.

In the present work, such classification was taken further, aiming to define a first step for an assessment of damaged masonry arch bridges under service loading conditions. The purpose was to present the railway administrations a clear methodology that allows them knowing how to proceed based in the results of the bridges surveys included in the routine maintenance. With that purpose in mind, a four level damage classification based in the previous classification has been performed. Each level has associated a different analysis strategy or assessment procedure. These new four levels are described below:

Group 1: Damage with no structural incidence. Although they can be called damages, their origin is not caused by a bad strength behavior and their intensity and potential effects do not affect the bearing capacity of the bridge, so despite maintenance works have to be done, no structural assessment is necessary. Fig 1 shows some examples of these damages.

Fig. 1. *Stains, crusts, efflorescence, vandalism, etc.*

Group 2: Damage with no strength origin but that need of “classic” structural assessment. Some of the damages that come from a bad durability performance can affect the strength behavior, so some structural assessment is necessary. In this case, the intensity and potential extension of these damages has to be taken into account, by modifying the geometry and mechanical parameters of the different structural elements. Their representation can be done using both 2-D and 3-D analysis as well as they can be assessed performing Ultimate Limit State studies, although some service loading analyses are also recommended. Fig 2 shows some examples of these damages.

Fig. 2. *Loss of material from joints and pieces, vegetation, previous interventions, etc.*

Group 3: Damage with strength origin which need of structural assessment. Damages are pointing out that there are some problems with the local or global strength mechanisms of the structure. Local and global specific assessment is needed. Such assessment normally requires clarifying the damaged bridge 3-D behavior, which can be faced monitoring the structure, conducting 3-D numerical analyses incorporating the damage in the analyses or any other known method that sheds light on the longitudinal and transverse damaged bridge behavior. Fig 3 shows some examples of these damages.

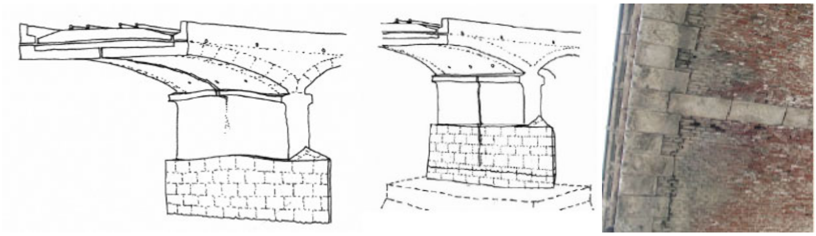

Fig. 3. Longitudinal and transversal cracks in the vault, vertical cracks in piers and abutments.

Group 4: Damage with high structural incidence. These damages are similar to those classified under Group 3, but implying a higher level of risk. The presence of these damages indicates the necessity of conducting an Emergency assessment which lead to preventive or rehabilitation measures. Fig 4 shows some examples of these damages.

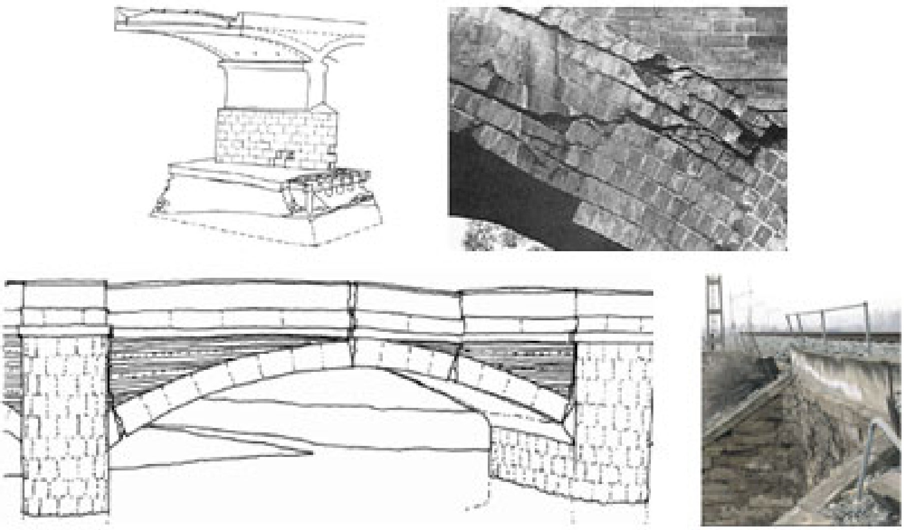

Fig. 4. Scouring, mechanical failure of the masonry, arch mechanisms, spandrel bulging, etc.

3. SECONDARY ASSESSMENT – DAMAGE IMPACT ON THE SERVICE BEHAVIOUR OF MASONRY ARCH BRIDGES

As result of the preliminary assessment, it has been concluded that there are certain damages which presence is announcing an anomaly in the behavior of these structures. Besides being true that their presence does not seem to put in risk the bridge structural stability, their evolution within time can generate bigger problems. The existence of many bridges currently in service presenting these damages, without really knowing their real impact on the bridge behavior, leads to considering important defining how to have them in consideration in the analysis.

3.1. Group 1 and 4 damage impact on the structural behavior

The preliminary assessment defined above, allows concluding that those structures that present damages belonging to Group 1 and 4 do not need structural assessment. Ones because they just imply maintenance works and the others because they require implementing emergency measures.

3.2. Group 2 damage impact on the structural behaviour

Those structures that present damages defined under Group 2, can be evaluated undertaking the structural assessment most commonly performed to these structures, which just involves an Ultimate Limit State analysis. The particularity that this study has is that the damages need to be implemented. Such implementation is performed by considering a decrease in the section where the damages arise, by decreasing the material properties or both ways simultaneously.

The performed studies, where the most common types have been analyzed, have shown that, unless there has been a major section loss or a major mechanical properties loss, the ultimate behavior gets barely affected. In any case, it is interesting to know how the presence of these damage has varied the safety factor with respect to the healthy structure. Moreover, the performance of analysis under service loading conditions can be recommended, which may reflect a slightly higher influence in the bridge behavior.

3.3. Group 3 damage impact on the structural behaviour

Bridges presenting this type of damage have violated their service conditions, understanding these as those where the original structural stiffness is kept. Once a crack appears, the structure’s stiffness distribution is modified and its functioning becomes unknown. Besides being structures which have got many post critic mechanisms and not implying an imminent collapse, the mid - term evolution of these damages and their concomitance can imply an unbounded risk.

Therefore, their existence should not be taken lightly and should be particularly studied. In order to try shedding light on the behavior of masonry bridges presenting these damages, these were studied using a different approach than the classic one used till nowadays by most of us.

This study consisted in conducting 3-D analysis under service loading conditions, representing the ideal situations (healthy structures) and the real situations (damaged structures with damages belonging to Group 3).

Regarding the damage implementation, Group 3 damages are not consequence of a durable cause, which may result in loss of section or in a decrease of the material properties. They are cracks that can appear in different elements of the bridge.

Analyzing these damages, one can see that all of them can be represented as a combination of horizontal and vertical cracks. In the undertaken study, the cracks were represented as if they were passing through; to observe the behavior in the worst possible case. This was considered especially important due to the fact of being difficult to determine the depth of the crack.

The different types of cracks analyzed are now listed and represented in Fig 5.

1) Longitudinal cracks in the vault-spandrels contact.
2) Longitudinal crack at the center of the vault.
3) Longitudinal crack under the train load.

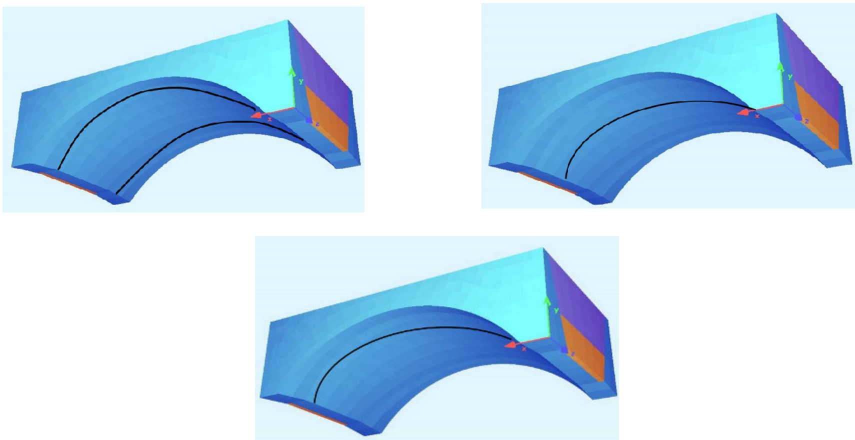

Fig. 5. Types of cracks studied. Vault Extrados view.

Due to the fact that the analysis undertaken was performed under service loading conditions, the traffic loads considered were those proposed in [1], which basically coincide with Eurocode Type 1 load pattern as passenger load and Eurocode Type 5 load pattern as freight train load.

The followed methodology consisted in comparing the analysis undertaken for healthy structures with those performed with damaged structures. This allowed determining the possible influence of the different damages that a bridge can present.

When comparing the healthy analysis with the real analysis with the damages belonging to Group 3 implemented, special attention was payed to Peak and Mean Stresses in addition to their distribution. Although the stress variable has not got the same meaning in masonry structures as it has for concrete and steel structures, it has been taken as an indicative variable.

For identifying this variation on the Peak and Mean Stresses, the following sections were studied carefully and compared:

- Longitudinal section through the middle point of the load application. It allowed viewing the longitudinal load distribution along the infill and along the vault.
- Longitudinal section at the spandrel - fill connection. It allowed understanding the collaboration of the spandrel to the load distribution and detecting if its limit was close to be exceeded with the consequences that this implies.
- Crown cross section. As consequence of being where there is less infill thickness, the loads get less distributed what implies particular high stresses. It

is one of the most susceptible areas to present tension stresses and hence cracks.

- Skewback cross section. This section was selected because of being an area where there is a concentration of different stiffness (backfill, infill and the vault), being an area of stress concentration.

The sectional study plus the overall 3-D view, aimed determining the load distribution on the structure as well as the stiffness variation, which allowed understanding how each of the bridge elements was behaving. It also allowed knowing the expected stress levels in each area, enabling the detection of potential tensioned points (cracks most likely to appear) as well as most stressed sections.

The analysis undertaken did not take in consideration fatigue parameters, which were studied in [7].

4. RESULTS FROM THE STUDIES UNDERTAKEN FOR QUANTIFYING THOSE DAMAGES WITH STRUCTURAL ORIGIN (GROUP 3)

1) The existence of cracks in the vault implied a change of the stress distribution, being such change greater for those cases in which the crack is located between the spandrel and the vault. Maximum stress areas are moved to the edge of the cracks, thus being its distribution less concentric and symmetrical.

   The following figures Fig 6, 7, 8 and 9 present some diagrams showing the stress state of one masonry arch bridge in three different situations: healthy bridge, bridge with a longitudinal crack between the spandrel and the vault, bridge with a longitudinal crack in the center of the vault and bridge with a longitudinal crack under the train load. Although the models have taken into account the effect of the filling, the presented views, have the filling removed for having a better view of the stresses in the masonry.

Healthy model:

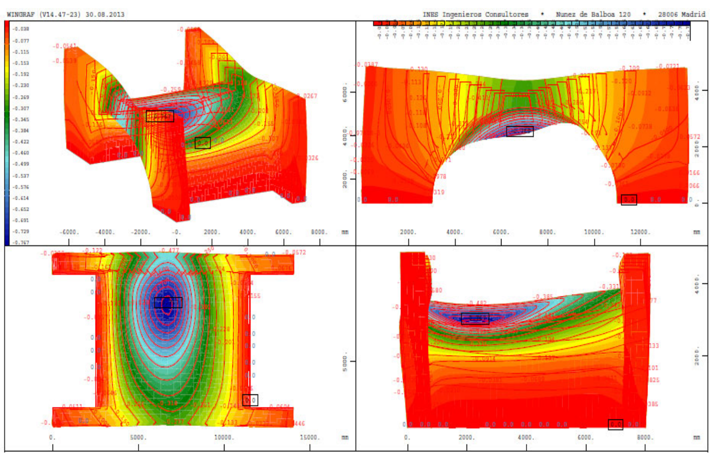

Fig. 6. *Vault and spandrels deflections. Different views. Units in mm.*

Model with a longitudinal crack between the spandrel and the vault:

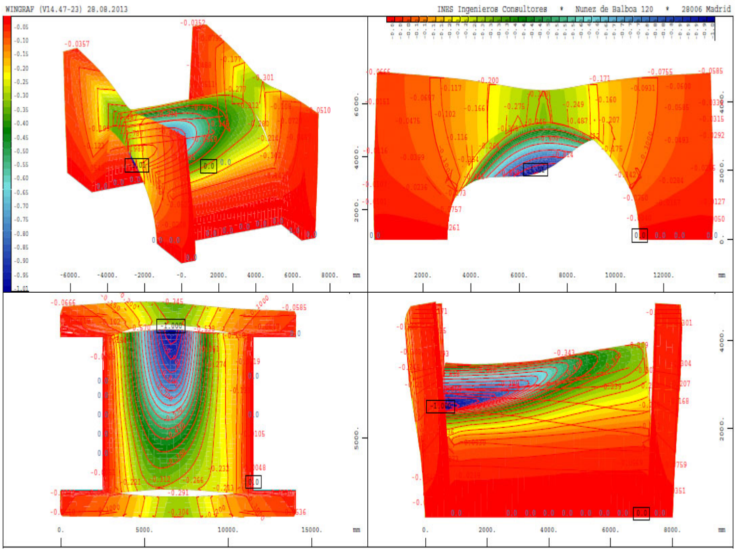

Fig. 7. *Vault and spandrels deflections. Different views. Units in mm.*

Model with a longitudinal crack in the center of the vault:

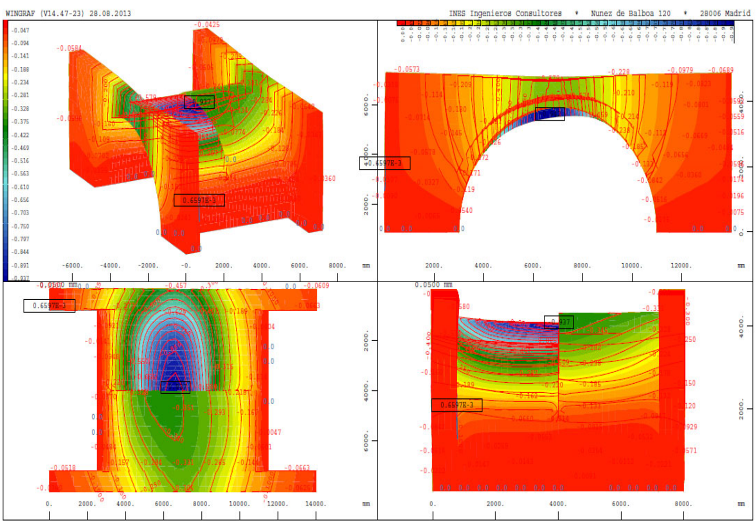

Fig. 8. *Vault and spandrels deflections. Different views. Units in mm.*

Model with a longitudinal crack under the train load:

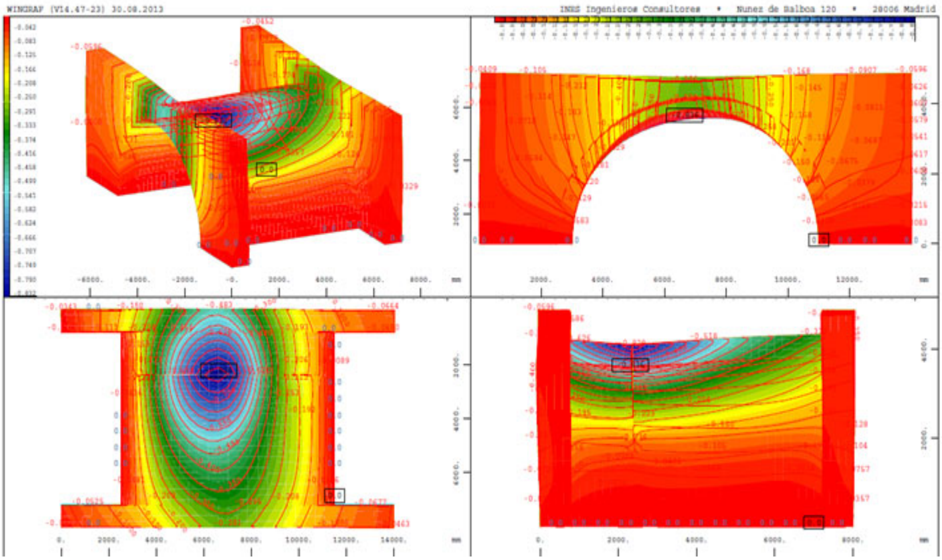

Fig. 9. *Vault and spandrels deflections. Different views. Units in mm.*

2) The existence of cracks at the vault, increases the Peak Stresses up to a 60% in some cases but barely up to a 10% in others.

   Besides the Peak Stress increase, in each case, the most unfavorable section varies significantly. Peak Stresses variation can reach up to 40 % at the key section. At the skewback section, these values vary slightly upwards, having a Peak Stress variation which can reach up to 60%. These variations get reduced in a 50 % if the vault cracks are not localized between the spandrel and the vault but in the middle of the vault or under the applied load.

   The explanation to the difference of stress increase between the skewback and the key section is related with the effective width. As it can be seen in Fig 10, in the case where the bridge has got a crack between the spandrel and the vault, the effective width decreases considerably in the Skewback sections, while the Key section remains with more or less the same effective width. Therefore the Skewback sections are more stressed and the variation of the Peak Stress is more noticeable.

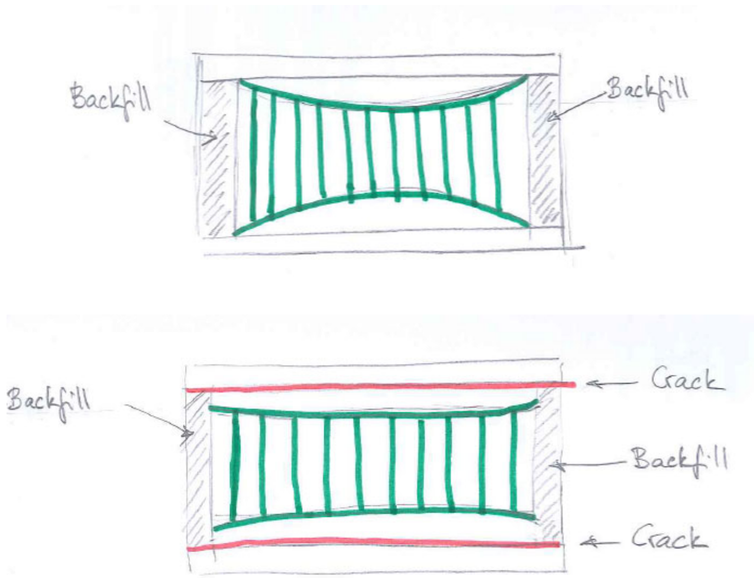

Fig. 10. *Variation of the effective width.*

Depending on the spandrels stiffness and the effectiveness of its connection with the vault, the effective width will be larger or smaller. In the case where the spandrels do not cooperate by the presence of cracks, the path followed by the load is much straighter, being this way its effective width reduced. As mentioned before, this effect has major implications for Skewback sections.

In addition, it should be noted that the contribution of the spandrels is much higher at the Skewback sections than at the Key section.

3) When speaking of Mean Stress, the variation due to the presence of cracks in the vault implies an increase around 20 to 30 % from the values obtained for the Healthy analysis.

4) It is remarkable how the presence of a crack under the train load has little influence in the longitudinal behavior. This is because the two semi vaults are able of working independently, as it is shown in Fig 11.

5) The reaction distribution is slightly affected by the separation of the vault and the spandrel. This crack softens the peak of horizontal and vertical reactions at the spandrels of the healthy analysis.

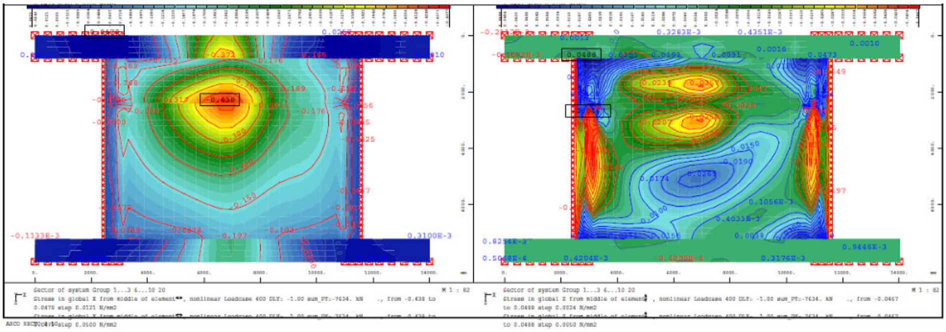

Fig. 11. *Vault and spandrels Stress. Left: Longitudinal stress at extrados. Right: Transversal stress at the extrados. Model with longitudinal crack under the train load. Units in MPa.*

5. CONCLUSIONS

5.1. Contextualization

The masonry arch bridges are being assessed from the point of view of their failure (ULS), featuring comfortable results indicating the high adaptability of these structures to the new operation conditions. Moreover, despite obtaining high values for their safety factor, numerous damage is found, which structural impact is not entirely known. This implies that currently the railway administrations are coexisting with these damages without a clear understanding of the risk they imply in the operating conditions at a Medium-Term.

The documents [1] and [2], aim raising awareness of the need to study these damages by performing an assessment of these structures considering the problems they actually present.

5.2. Damage classification

Based in the concept that masonry arch bridges are considered not to have violated the service conditions when they keep working as they were designed, that is, the stiffness path followed by the loads is the original one, a damage classification was carried out. Such damage classification includes in 4 groups all the damages that appear in these structures, according to their structural impact and location. Those damages which do not imply a stiffness redistribution have been included in Groups 1 and 2, while the rest are included in Groups 3 and 4. Besides this criteria, the damage classification definition can be summarized by:

Group 1 contains those damages which origin is not structural and which presence does not entail a structural impact are included.

Group 2 includes those damages with no structural origin but that have a structural incidence, requiring their consideration in the structural assessment.

Damages classified as Group 3, are those which have a structural origin as well as a structural impact and which consequences are not known.

Group 4 involves those damages with structural origin, which structural incidence endangers at a short-term the structure equilibrium.

5.3. Damage assessment

For performing a damage assessment of a masonry arch bridge, besides a complete knowledge of its internal and exterior geometry, a mechanical characterization of the materials with which it was built with and a study of the traffic it supports, a damage survey needs to be addressed, classifying them as just discussed.

Group 1 damages just imply maintenance works to be carried out on the bridge were they appear. As they have no influence in the structure's bearing capacity, no assessment is required.

The influence of damages classified as Group 2 and 3 in the structure behavior is unknown. When the ultimate limit state is studied, the presence of these damages barely affects the bearing capacity of these bridges. This is due to the fact that these structures present many post critic situations before reaching collapse. Therefore, it is considered important to study the impact of these damages under service loading conditions in order to have a better understanding of the bridge behavior.

The methodology followed for assessing these damaged bridges consisted in comparing the ideal situation with the one having the damages implemented. Group 2 damages were implemented by reducing the section where they appear or by decreasing the mechanical properties of the material in which the damages are present. Group 3 damages can be represented by the combination of horizontal and vertical cracks.

Group 3 damages require specific analysis: monitoring of existing structures, more complex numerical analysis in order to shed light on the structure behavior under service loads rather than its ultimate behavior to be able to take decisions.

Damages classified as Group 4 imply a short – term collapse risk of the structure so they require immediate repair.

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