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STRATEGIES FOR THE NONLINEAR SEISMIC MODELLING OF MASONRY BUILDINGS IN AGGREGATE

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Abstract: *The paper presents a study about the strategies for the numerical modelling and analysis of masonry buildings in aggregate, a complex configuration typically encountered in Italian historical centres in which structural units are built in continuity next to each other and that is often characterized by a high irregularity, both in plan and elevation. The complexity of morphological articulation, especially in the case of historical masonry, is combined to the inherent difficulties associated to the modelling of masonry, which is a composite, highly inhomogeneous and anisotropic material, characterized by significant nonlinear, irreversible, and dissipative phenomena in the mechanical response, which should be adequately accounted for in a structural model. Some case studies of masonry building blocks representative of real configurations which can be found in Southern Italy (Puglia) have been numerically modelled by a detailed 3D FEM approach, assuming a nonlinear constitutive model with plasticity and damage for masonry. In order to investigate the influence of uncertainties and incomplete knowledge, different models have been analysed, by varying some of the main geometrical and mechanical parameters, performing preliminary modal analyses and a set of nonlinear time history analyses. In particular, the influence of floor deformability on structural response was investigated, first in the linear field, by analyzing the variation of modal parameters, and then through a set of dynamic analyses with natural accelerograms, in terms of damage distribution.*

Keywords: *Masonry buildings, aggregate buildings, seismic modelling nonlinear dynamic analysis, damage.*

1 Introduction:

The Italian territory is characterized by a medium-to-high seismic hazard, which, combined with the high vulnerability of the existing building stock, makes the issue of risk management and risk reduction strongly felt, as widely acknowledged by the scientific and technical literature (Mezzina et al., 2008). Indeed, it should be remembered that more than 70 percent of the existing buildings on Italian territory were built without following any seismic requirements. In most cases, we are talking about historic masonry or reinforced concrete structures that, due to inherent static deficiencies or degradation due to poor maintenance, are particularly prone to damage in the presence of seismic actions.

Among the components of society that are endangered by natural disasters such as earthquakes - human lives; built environment; infrastructures; strategic economic and organizational activities; social cohesion; symbolic cultural and social elements - the building heritage, in which Italy is particularly rich, constitutes a very important element. This includes not only monumental buildings, but also the many historic centers which constellate the Italian territory and represent for local communities an invaluable and precious asset, since they are the symbolic and irreproducible incarnation of their cultural identity. For these, in addition to the risk in terms of human lives, there is a loss of an intangible nature that is very difficult to quantify economically.

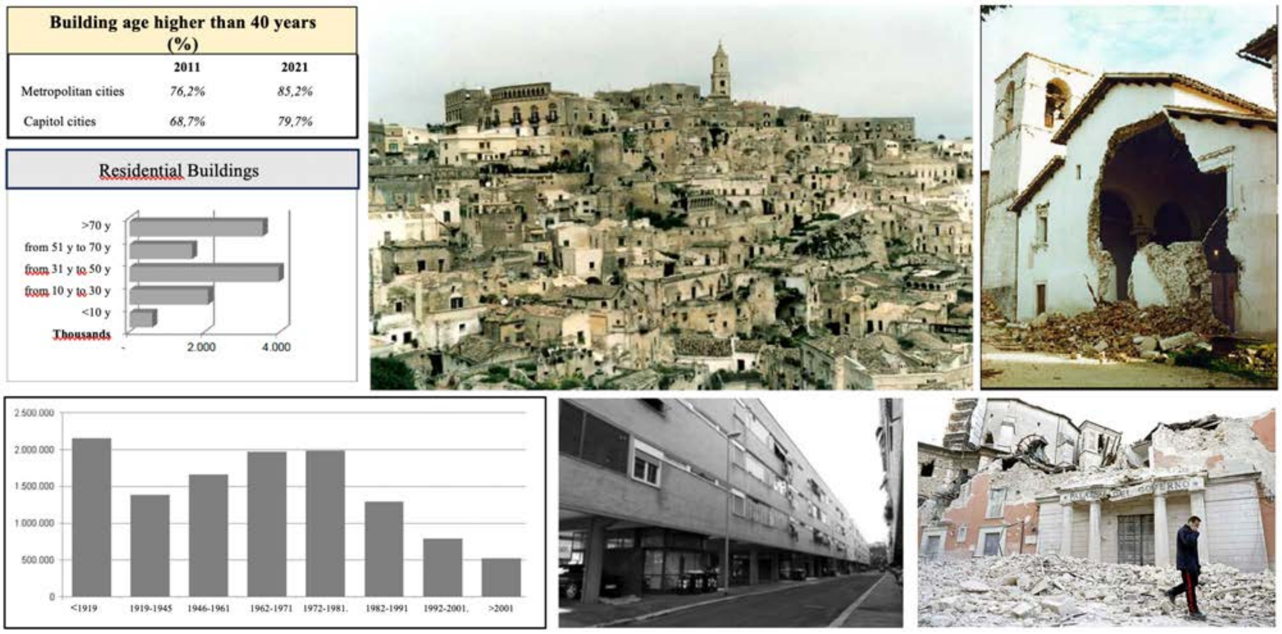

Figure 1: Distribution of the age of construction of residential buildings in Italy (Cresme, 2013).

Among the various components of society that are endangered by natural disasters such as earthquakes - human lives; built environment; infrastructures; strategic economic and organizational activities; social cohesion; symbolic cultural and social elements - the building heritage, in which Italy is particularly rich, constitutes a very important element. This includes not only monumental buildings, but also the many historic centers which constellate the Italian territory and represent for local communities an invaluable and precious asset, since they are the symbolic and irreproducible incarnation of their cultural identity. For these, in addition to the risk in terms of human lives, there is a loss of an intangible nature that is very difficult to quantify economically.

From a constructive point of view, historic centers include buildings whose structure is mainly in ordinary load-bearing masonry, and which are the result of successive growths, stratifications, morphological and material alterations occurred over time, often in an uneven and chaotic manner, as it is well recognizable today in the peculiar textures of historic urban fabric. Throughout Italy, in fact, historic centers are typically characterized by a conformation of the urban fabric, morphologies, arrangement of aggregates and streets that escapes any descriptive rule. Such features of inhomogeneity, irregularity and lack of qualified and reliable construction processes mean that, as a matter of fact, the "ideal" masonry building, as defined by in present codes or in the ancient “rule of art” is an exception rather than a rule (Fig. 2).

Even for an ideal building, modeling the mechanical behavior of masonry is one of the most complex and challenging problems in modern structural engineering (Uva e Salerno, 2006). In fact, masonry is a composite, highly inhomogeneous, and anisotropic material (especially in the case of historic masonry), and its mechanical response is characterized by significant nonlinear, irreversible, and dissipative phenomena, which must be adequately accounted for in a structural model aimed at accurate prediction of ultimate load and response to cyclic loads. Many of the relevant mechanical phenomena (such as interlocking effect between blocks, frictional creep at joints, nucleation and crack growth within mortar joints or mortar-brick interfaces) actually occur at small or very small scales and would therefore require the development of extremely detailed models. On the other hand, the overall response of the masonry building to vertical and horizontal actions is governed by its overall geometric and morphological configuration. For example, the distribution of loads among the different vertical structural elements is profoundly affected by the regularity of the structural organization in plan and elevation and by the effectiveness of the box-like behaviour.

Figure 2: The "Ideal" masonry building and regular, schematic forms of aggregations.

Studies and research in this field, therefore, have attempted to address this complexity with different strategies aimed at modeling and detailed analysis of the structural response of masonry buildings. The different classes of methodologies, briefly recalled below, are all characterized by the presence of refined numerical procedures, with high computational effort, and by the need to provide in situ investigations for in-depth and complete knowledge of structural, geometric, and mechanical characteristics, resulting in high time and economic cost (Leggieri et al., 2021]:

- Fully discrete models, which involve detailed micro-modeling of each component (blocks, mortar joints) and their interaction, using appropriate constitutive laws. Considering the high computational burden, application is generally limited to the analysis of individual masonry elements.
- Continuous models, which model masonry as an equivalent deformable homogeneous continuum whose nonlinear constitutive laws are derived through appropriate homogenization techniques.
- Rigid block and spring models, in which a process is carried out to transform the original solid into an equivalent system consisting of a set of rigid bodies connected by springs, where the nonlinear mechanical response is concentrated, with appropriate constitutive laws.
- Macro-element models, in which the masonry building is described by an "equivalent frame" consisting of elements of various types: panel, nodes, lintels, etc.).

It should be emphasized that all these approaches, because of their complexity, the need of in-depth input data and high cost of the analyses, are suitable for the seismic assessment of individual buildings but absolutely unfeasible, in the practice, at the urban scale, when a large number of buildings has to be handled.

In the case of historical centers, a further problem is the typical morphology of the urban fabric, which consists mainly of building clusters generated by successive extensions and additions over the years, that amplifies the conditions of plan and elevation irregularity.

Figure 3: Irregularities of building aggregations in the urban fabrics of some historical centers in Southern Italy (from top: Molfetta, Altamura; Matera).

These circumstances make it difficult (or in some cases impossible) to base the analysis of the structural performance of the entire building stock on the knowledge (however accurate) of the geometric, morphological and structural characteristics of a single structural unit that is part of a larger aggregate. In general, the assessment of seismic vulnerability of masonry aggregates in historic centers is conditioned by many aspects:

a) Difficulty in achieving a sufficiently thorough and complete knowledge of the structural and typological characteristics of each individual structural unit.
b) Difficulty in identifying the actual interactions between the structural units within the aggregate to be analyzed.
c) Need to implement numerical models extended to all the units of the aggregate and perform complex analyses, requiring considerable computational burden and time.
d) Unavailability of real case studies or experimental tests to validate and calibrate numerical models.

To overcome these difficulties, simplified methodologies are needed that can handle the large amount of data required and reduce the computational load required for modeling and analysis of masonry aggregates with adequate accuracy and reliability of results. The approaches generally adopted fall into two categories:

- Modeling and analysis of the individual structural unit extrapolated from the aggregate context, taking into account any interactions due to structural contiguity through appropriate modeling of boundary conditions.
- Modeling and structural analysis of the entire building aggregate "as is."

In both cases, detailed analytical models are developed, which of course can be implemented in cases where sufficiently complete information is available, in order to reduce parameter uncertainty and obtain accurate results. Whenever a technician is called upon to assess the vulnerability of a building in a historic center, which in the vast majority of cases is not isolated but included within an aggregate, he or she will be faced with the problems briefly outlined, while also having to deal with the limitations - including economic ones - arising from an assignment confined to the individual building unit. The first question that arises in such cases is whether it is necessary to consider, in the analyses, the actual conformation in aggregate, and if so, what are the relevant interactions between the building under consideration and the adjacent ones, and what is the modeling strategy and possible simplifications to be adopted: in fact, it is not necessarily the case that the most effective model is the most complex and detailed one. In summary, the operational path to be developed goes through the definition of three fundamental - Identification, within the aggregate, of the "structural unit" (which could include larger or smaller portions of adjacent buildings) on which to focus investigation, modeling, and analysis, balancing appropriately the needs for completeness and accuracy with the data actually available and the objectives to be achieved:

- Identification of significant interactions of the selected structural unit with the rest of the aggregate.
- Definition of acceptable simplifications in modeling aspects.

2 Seismic analysis of a representative case study of irregular building aggregates in Puglia

The choice of a representative case study was based on data collected as part of some research on the regional seismic vulnerability assessment of the built heritage of the historic centers of the Province of Foggia (Puglia, southern Italy), whose general objective was to develop multilevel methodologies and tools for the seismic vulnerability assessment of the regional territory (Uva et al, 2016; Casolo et al, 2017a).

The case study adopted is an aggregate located in the municipality of Sant'Agata di Puglia, very typical of the geographical context of the mountainous areas of Puglia, built on a slope with a strong difference in height between the two main fronts, characterized by a tapered planimetric shape, similar to a very elongated rectangle. A series of modeling and advanced numerical analyses were carried out, aimed at understanding the overall behavior of the aggregate and the effects on individual structural units. The shape of the aggregate is rather regular in plan, as can be seen in the ground-floor section shown in Figure 4, whereas it is irregular in elevation due to the different ground levels and the different heights of the structural units (Figure 4, right).

Figure 4. Plan view and section of the historical center of Sant'Agata di Puglia, with the location of the case study (left); North and South views of the case study, showing the difference in height between the main fronts.

Overall, a situation of high irregularity is evident due mainly to three factors:

- Strong unevenness in the setting plane of the foundations.
- Irregularity in the arrangement of the openings along the facades facing the main streets.
- Interventions after construction: joining or partitioning of the original units, addition in elevation.

The geometry of the building aggregate was known from a laser-scan survey, basing on which the three-dimensional finite element models of the entire aggregate was developed by using the software Abaqus (Abaqus, 2023).

To this aim, the overall geometry of the unit complex was simplified as much as possible, both to contain the number of variables in the numerical problem and to facilitate the subsequent interpretation and processing of the results obtained. Since the geographical context is characterized by the presence of significant slopes, with offsets of the ground plane and significant irregularities in elevation, the numerical FEM model includes an adequate significant volume of soil and proper strategies to represent possible effect related to dynamic soil-structure interaction (Casolo et al. 2017b).

2.1 Modal analysis

Preliminarily, the dynamic response in the elastic field was analyzed for the complete aggregate and the representative volume of ground, defining two types of structural materials: vertical structures, consisting of limestone masonry and characterized by an orthotropic constitutive law (mass density =1800 kg/m3, Young's Modulus E=900 MPa for all directions; Poisson's ratio=0.05; Shear Modulus G=150 MPa for all directions); floor and roofs characterized by an isotropic constitutive law (Young's Modulus E=3000 MPa; Poisson's ratio =0.05; mass per unit area 300 kg/m2). The orthotropy of the vertical structures has been exploited in order to define a shear deformability much lower than the one theoretically allowed in the case of isotropic material. The results of the modal analysis for the first three modes of vibration are shown in Figure 5.

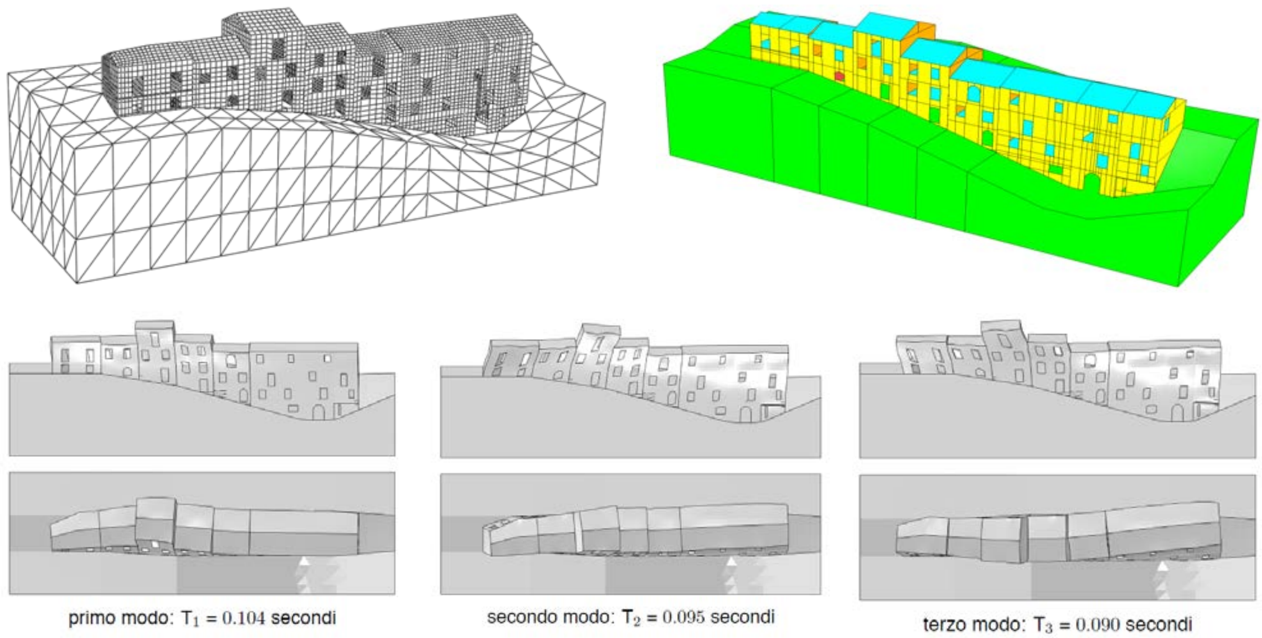

Figure 5: Top: the FEM Model of the building aggregate. Bottom: the first three vibration modes.

The modal analysis shows that there is no single mode of vibration that can engage the entire building aggregate, due to the geometric complexity and various irregularities present in the elevation. The first three modes of vibration are the most significant, as they involve most of the participating mass, and from their analysis it can be observed that the end buildings are the most prone to damage. Significant damage can also be observed at the top of the most prominent building, where the height irregularity is concentrated, and at the openings, which in fact always represent a critical point.

2.2 Nonlinear dynamic time-history analysis

From a theoretical point of view, considering the high geometric irregularity and strong mechanical nonlinearities of the masonry material, the most suitable approach to analyze the seismic response is the nonlinear dynamic time-history analysis, by modeling the nonlinear cyclic behavior of the masonry and considering as dynamic input accelerograms appropriately selected to be representative of the seismic hazard of the site.

This procedure was applied to the numerical model of the Sant'Agata building aggregate, assuming for the masonry the CDP (Concrete Damage Plasticity) of the Abaqus library, wish is a nonlinear hysteretic model, and considering as input a group of 2 accelerograms applied simultaneously in two orthogonal directions of the horizontal plane (coincident with the transverse and longitudinal direction of the aggregate). The vertical component of the earthquake, of little relevance to the type of structure under consideration, was neglected. The accelerograms were chosen to be spectrum-compatible with respect to the LS Limit State for the municipality of Sant'Agata.

The nonlinear dynamic analysis on the full spatial model confirmed that the damage tends to be concentrated at the irregularities, i.e. the end buildings and the tallest one, as well as the areas near the openings (Figure 6).

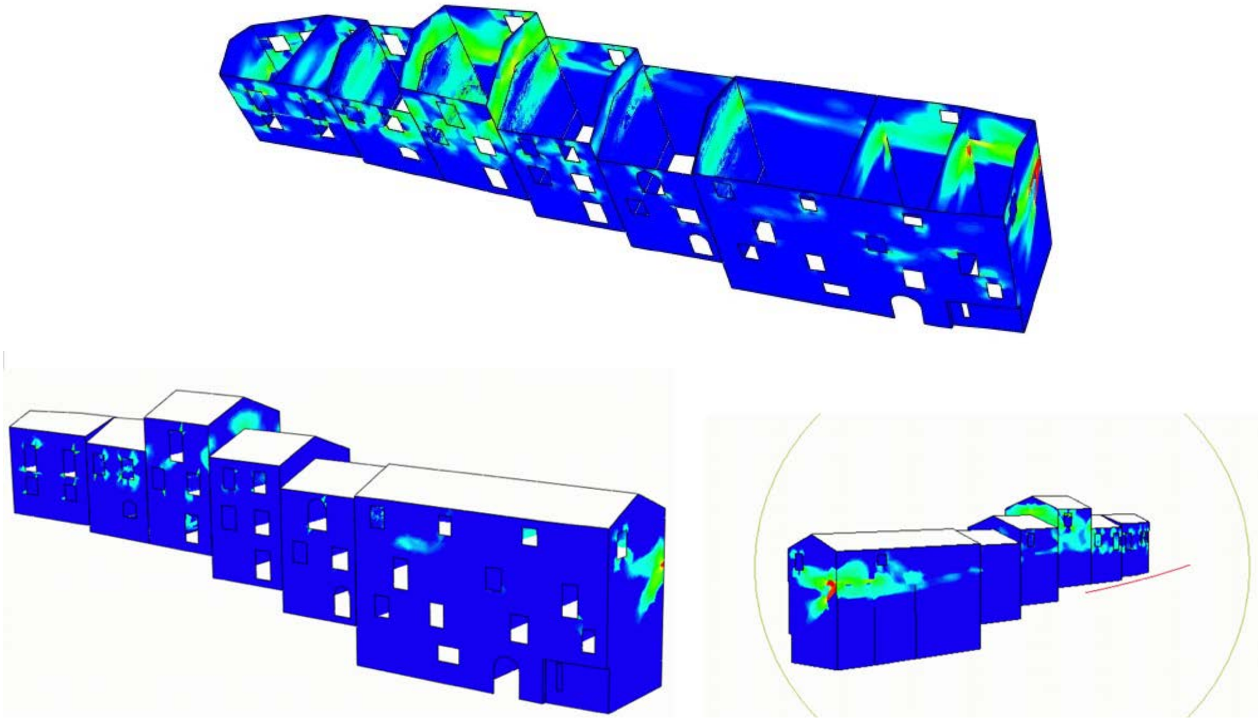

Figure 6: Damage distribution from the nonlinear dynamic analysis.

2.3 Simplified modeling

Once the most critical parts of the aggregate have been identified, which are generally those characterized by irregularities, geometric or construction anomalies (an operation that can be effectively performed through preliminary linear analyses, as seen before), a possible strategy is to restrict the detailed nonlinear dynamic analysis to a few representative sections of the aggregate, even with a plane model. For the case study, this was done by adopting a RBSM modeling approach (Casolo, 2009; Casolo et al. 2017a), which allows time-history analyses to be done very efficiently and thus also in large numbers, with different accelerograms, to reduce uncertainties about the actions.

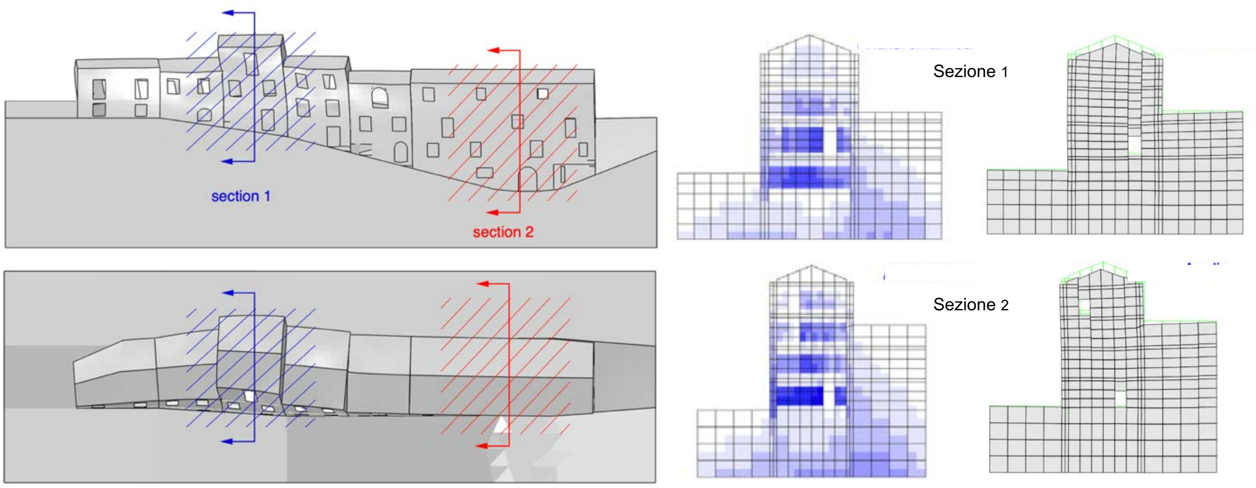

Figure 7: Simplified plane models of the two critical Structural Units: Section 1) and Section 2) and damage distribution

In Figure 7, an example of the results of the nonlinear dynamic analysis performed for two plane models, corresponding to two critical sections of the building aggregate is shown, in terms of map of the vertical stress and deformed shape at the end of the analysis.

3 Concluding Remarks

Managing the analysis of a historic masonry building means in most cases dealing with a very high level of complexity, since such buildings are systematically an integral part of larger aggregates, and the difficulties and uncertainties that always characterize the analysis of an existing building are worsened by the need to extend the field of investigation, to adjacent building units and model possible interactions.

It is not possible to outline a standardized path, valid for all situations, to address the many critical issues that arise, however, it is possible to identify some essential strategic elements for selecting the most suitable modeling and analysis approach among the many available. Pursuing the realization of the most extensive, complex and detailed model possible does not always lead to results that are actually more accurate, but may, on the contrary, be only illusorily more realistic, if there is not an adequately exhaustive and accurate level of knowledge at the base. Moreover, the cost-economic and time-of the investigations required to reach that depth is often incompatible with any cost-benefit balance, when not entirely operationally impractical. In the case of aggregate buildings, remembering that the focus is on verifying the safety of individual US, not the entire aggregate, it is important to recognize significant interaction effects and represent them with even simple but effective diagrams in the structural model, possibly even testing different modeling assumptions.

4 ACKNOWLEDGEMENTS

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ABAQUS. The Abaqus Software is a product of Dassault Systèmes Simulia Corp., Providence, RI, USA. © Dassault Systèmes, 2023.

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