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Simplified building models as advanced seismic screening tools for steel industrial buildings

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ABSTRACT

The paper investigates the suitability of simplified building models to be used as advanced screening tools for the seismic vulnerability assessment of older industrial steel buildings. The considered buildings have been built before the enforcement of modern seismic codes and they are characterized by joints with low ductility and by the absence of capacity design provisions. In addition, such buildings, characterized by a wide plan extension, are typically part of large industrial areas. The complex geometry of the buildings makes the creation of a complete finite element model difficult. This is due to the high number of degrees of freedom and to the consequent high number of vibration modes to be included in a general response spectrum analysis. To overcome such limitations, simplified building models for advanced seismic screening are herein proposed and compared to traditional vulnerability procedures. Such procedures may be used for a first estimate of the seismic vulnerability of older and large industrial buildings, in order to identify and quantitatively rank seismic deficiencies before a detailed assessment. The validation shows that the investigated approaches are particularly suitable for seismic risk assessment of building portfolios and for providing a first estimate of the load demand in the elements of the lateral force resisting system.

1. Introduction

After the Emilia (Italy) earthquake in 2012, where many industrial buildings were damaged [1–4], a growing attention has been placed on existing plants. Old steel industrial buildings not designed following modern anti-seismic criteria are considered herein, with the purpose of preserving human life and avoiding the downtime and losses caused by possible future seismic events. Such buildings present a wide plan extension, a structural layout typical of the Italian pre- and post- World War II period, a general low ductility of the connections and the absence of capacity design provisions.

The main structural elements are typically riveted built-up members connected by means of bolted connections. Runway beams are placed in the longitudinal directions to support overhang cranes; these beams are typically made by truss members or by assembled I-shape beams. Due to the large distance between adjacent columns (> 20 m), the bracing is provided by inclined elements connected to the crane runway beams or by stiffer columns in the longitudinal direction. In the transverse direction, the columns act as cantilever elements. The roof is supported by lattice beams spanning in the transverse direction, which are typically supported by lattice girders connecting adjacent columns or supported directly by the crane runway beams through vertical elements. The roof diaphragm action is provided by cross bracing spanning in the longitudinal and transverse direction. Fig. 1 shows some examples of typical details of such buildings.

To assess the seismic vulnerability of existing buildings, reference can be made to the methodologies found in national and international building codes (D.M. 14/01/2008, EN 1998-3:2005, FEMA 356) [5,27,6], which follow worldwide recognized seismic design methods and involve linear and non-linear procedures. The main target of such procedures is the definition of a building seismic vulnerability index, which is obtained by considering the overall behaviour of the structure and by comparing the seismic demand and capacity of the elements and the connections. However, the extensive plan dimension of the considered building typology requires much more effort for the creation of the finite element model compared to smaller buildings, due to the high number of elements and associated degrees of freedom. This leads to a high number of vibration modes to be considered and to a subsequent high computational demand. In addition, in the case of wide industrial buildings, extensive industrial areas or large portfolios, seismic screening procedures are more appropriate for a preliminary seismic risk assessment and management, as required in the industrial and insurance fields. Therefore, simplified screening procedures are more appealing.

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At this regard, it is worth referring to the work of Petruzzelli [7] who suggested tackling this problem at different scales as a function of the number of considered buildings, namely "large-scale", "meso-scale", and "site-specific scale". The "large-scale", involving hundreds or thousands of buildings, in which only a general and preliminary assessment is carried out by comparing the seismic capacity of the building with the seismic demand according to the building code enforced at the time of construction. In the case of sites which were not classified as seismic-prone in the past, it is possible to compare the actual seismic demand with the wind load demand at the time of construction. The main purpose of the "large-scale" approach is to act as a decision-making tool enabling the rational ranking of priorities, identify needs of more advanced analyses, or to plan possible retrofit interventions and mitigation measures. Such an approach could be categorized as a type of "seismic screening". The "meso-scale", involving buildings of a specific industrial area, in which a fragility curve is defined for each structure or class of structures in the portfolio; this allows evaluating the expected seismic losses. The fragility curves could be appositely developed or inherited from past projects [8,9]. The "site-specific scale" involving the analysis of a single building, in which conventional seismic analyses, as non-linear dynamic analyses, are carried out on a complete model of the building to obtain the failure probability [10,11].

The present paper investigates two simplified building models suitable for a first estimate of the seismic vulnerability of the industrial buildings under investigation. In both cases, linear elastic analyses are conducted. The first approach considers planar models of the building and it requires a limited number of elements. The procedure allows estimating the load demand on the elements of the lateral force resisting system, namely vertical and horizontal bracing. The second approach considers a three-dimensional model of the building. Auxiliary elements with equivalent stiffness and mass are included in the model to significantly reduce the number of elements, degrees of freedom and, consequently, modes of vibration required in a response spectrum analysis. Following the categorization of Petruzzelli [7], such approaches may be included in the "site-specific scale", because they require the knowledge of specific buildings. Nonetheless, the proposed simplified building models, allowing for an advanced seismic screening by means of linear analyses, do not require the definition of computational-demanding fragility curves and therefore they could be adopted at the "*meso*" and "*large*" scale, especially in the case of recurrent structural layouts and recurrent details in different geographical areas.

2. Seismic screening and vulnerability assessment of existing industrial buildings

2.1. Seismic screening

Seismic screening is a preliminary structural assessment tool. It has the advantage of highlighting potential seismic deficiencies and it is adopted both to rank the seismic vulnerability of buildings among a portfolio and to get a preliminary estimate of the seismic risk of a given building. FEMA 154 and ASCE/SEI 41 are examples of seismic screening procedures [12,13].

FEMA 154 [12] provides a procedure for a rapid visual screening and ranking of buildings in seismic prone areas. The procedure is mainly intended for relative risk comparison among large groups of buildings and for prioritization of further studies and analyses. However, such procedure can also be used for a quick assessment of the potential seismic performance of a given building. A visual inspection of the building is the first step required by the procedure. The seismic-force-resisting system and any characteristic that might influence the expected seismic performance are identified. Given the building structural system, a score is assigned based on the level of seismicity of the region in which the building is located. Such score reflects the likelihood that a typical building of a given typology would sustain damage to such an entity beyond which life safety begins to become a serious concern. The score is then modified based on building attributes or site features that may increase or decrease the seismic vulnerability, such as the number of storeys, vertical or horizontal irregularities and the soil type. Finally, a structural score for the building is obtained, ranging between 0 and 7. The highest scores correspond to a better expected seismic performance.

ASCE/SEI 41 [13] defines a three-tiered process for seismic evaluation. Each successive tier is characterized by an increased effort and by a greater confidence in the identification and confirmation of any seismic deficiency. Tier-1 regards the seismic screening, Tier-2 deals with a deficiency-based evaluation procedure and Tier-3 refers to a systematic evaluation procedure.

Tier-1 and Tier-2 are intended for buildings belonging to defined typologies referred to as "common building types", but are inapplicable to the structural typology under investigation. Tier-3 is intended to cover all other building typologies, thus applicable to the investigated typology but requiring refined analyses. The literature survey emphasises the need for simplified evaluation procedures to be referenced to in the case of large industrial buildings.

Similarly to FEMA 154, Tier-1 requires the completions of quick checklists for each building type, including information on the presence of a complete load path for inertia loads, the redundancy of the lateral force resisting system, the possible influence of adjacent buildings, the presence of weak or soft storeys, the number of vertical or horizontal irregularities, the liquefaction susceptibility of the soil, the foundation configuration, and the type of non-structural components among others. After the collection of the data from all the checklists, the building deficiencies are summarized and the need for further analyses is highlighted. In Tier-2, all the potential deficiencies identified in Tier-1 are evaluated. Additional analyses are carried out to confirm each deficiency or to demonstrate the adequacy of the structure. Where required, the analysis of the seismic-force-resisting system shall be based on linear static or linear dynamic procedures. Tier-2 considers the evaluation of the potential deficiencies identified in the screening phase (Tier-1).

Other tools that might be adopted as seismic screening make use of fragility curves. At this regard, the project SYNER-G [9] developed a series of fragility curves to be used in risk assessment procedures. The project focused on the definition of harmonized typologies and taxonomies for European buildings, lifeline networks, transportation infrastructures, utilities and critical facilities. This approach has the advantage to provide a quick reference value for the seismic vulnerability. The high scatter of the results and the impossibility of detecting the most vulnerable elements represent the disadvantages of this methodology. The aforementioned project does not consider steel industrial buildings specifically.

2.2. Seismic vulnerability assessment

The existing seismic vulnerability assessment procedures (as in D.M. 14/01/2008, EN 1998-3:2005, FEMA 356 [5,27,6]) can be distinguished into linear and non-linear. Linear procedures can be subdivided into "linear static" and "linear dynamic" analyses. Non-linear procedures are represented by "non-linear static" and "non-linear dynamic" analyses.

As regards linear procedures, linear static methods are the simplest way to estimate the seismic response, although their applicability to the considered industrial buildings is generally limited to buildings regular in elevation. In the structural typology under investigation, the lateral stiffness of the structural element below the overhead crane is typically much higher compared to the elements supporting the roof structure. Linear dynamic methods, i.e. response spectrum analyses, allow considering and combining different vibration modes [14]. The linear dynamic approach follows an elastic analysis in which a behaviour factor is introduced to account for structural non-linearity as plastic hinge