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Seismic behavior of an industrial steel structure retrofitted with self-centering hysteretic dampers

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A B S T R A C T

The evaluation of seismic vulnerability of industrial constructions is a more and more relevant issue considering the damage occurred as consequence of recent earthquakes all over the world. Each industrial construction, on the other hand, has its own peculiarities depending on, for example, age of construction and aging, hosted industrial activities, structural and morphological modifications during its lifetime, and so on. In the present paper the seismic retrofit of an existing industrial steel structure is executed by using a steel self-centering device properly designed. To this purpose, a refined nonlinear model of the structure is developed, taking into account the most relevant aspects such as II order effects, global buckling of the elements, mechanical nonlinearities, etc. The seismic performances of the case study in its current, un-retrofitted, condition are so evidenced through several Incremental Dynamic Analyses. Afterward, the dissipative systems are introduced analyzing the influence on the global behavior of the several parameters defining the flag-shaped hysteretic behavior of the self-centering devices through several parametric nonlinear analyses. Particular attention is paid to the determination of the maximum and residual displacements and to the evaluation of the share of seismic energy dissipated by the dissipative devices and the one dissipated by the gravity structure. The results obtained allow a better understanding of the effects of seismic retrofit intervention through self-centering devices.

1. Introduction

Industrial facilities often store a large amount of hazardous material and, as reported in several studies [1] [2] [3] [4], the probability that accidental scenarios such as fire, explosion, toxic or radioactive dispersion may occur in the case of seismic event is very high. The ensuing disaster is sure to harm the people working in the installation and it may endanger the population living in the neighbourhood or in the urban area where the industrial installation is located.

Even if the content does not represent a direct threat to human lives or to the environment, damage to structural and/or non-structural elements can lead to huge indirect economic losses, as testified by the numerous studies on the survey of damage causes [5] [6] [7], by the special attention to the non-structural elements damage [8] [9] and to the speedup of community recovery [10] [11] after the 2012 Emilia (Italy) earthquakes. From this point of view, it is evident that, for industrial buildings, the scope of a retrofit/strengthening intervention should be the increasing of the "seismic resilience" [12] [13] rather than the reduction of "seismic risk", which is more appropriate for civil building [14]. It is therefore necessary not only to limit damages to structural and non-structural elements, but also to take into account, as a design parameter, the easiness and velocity of the repair work and the speed up of the production recovery.

From this point of view, supplying the structure with a re-centering capability, defined as the capacity of minimizing the residual displacement after the end of the seismic action, is an important aim when the increasing of the structural resilience is pursued.

Indeed, modern seismic design procedures allow inelastic deformation in dissipative zones during the earthquakes accepting some damage to structural elements. In this way, the dissipation of a relevant share of the seismic input energy and the adoption of smaller structural elements are permitted. But, on the other hand, repair works are needed after moderate-to-strong earthquakes especially in the case of substantial residual deformations [15].

Different strategies can be implemented to focus the inelastic deformation, and so the dissipation of energy, on suitable elements [16] [17] [18] [19] [20] [21]. In particular, for the retrofit of existing industrial plants attention is given to the use of passive dissipation systems, such as seismic isolation, see e.g. the recent work done by [22], and/or energy dissipation. The initial higher cost associated to a retrofit using seismic isolation or energy dissipation system, comprised the ones consequent to the adaptation of the non-structural elements (e.g. pipelines), will be likely compensate by the avoided losses in case of moderate-to-strong earthquakes.

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Traditional hysteretic devices, however, do not provide a real "active" re-centering force, resulting in the possibility of residual displacements at the end of the earthquake and in the consequent complication of the substitution operations, such as the need of flame cutting for the removal of dissipative elements [15].

In order to mitigate such problems, re-centering devices have been the object of ever increasing research studies ([23,24,25,26,27,28,29, 30]). This type of dissipative device is characterized by the presence of re-centering elements that mitigate, and may even eliminate, the residual deformations in buildings and/or residual forces in the dissipative devices after the seismic event independently from the displacement demand. The absence of residual deformation and of residual forces in structural elements leads to a simplification of the repairing activities, considered the great difficulties in assuring adequate safety levels for deformed structures and in the substitution of yielded structural element due to the presence of residual forces that complicate their disassembling. The introduction of re-centering dissipative devices can therefore leads to important reduction of the time required for the repairing of the industrial buildings and for the restarting of activities, increasing thus the building resilience.

The hysteretic force-displacement curve of such devices is typically characterized by a "flag" shape and, depending on the ratio between the re-centering force and the dissipative one, may present different values of the dissipated energy per cycle, residual displacement and residual re-centering force, as shown in Fig. 1.

The shape of the hysteretic curve is determined by 4 parameters, F_y, k_0, α and β, where F_y is the yielding force, k_0 the initial stiffness, α the ratio between the post-yielding and the initial stiffness, while β reflects the energy dissipation and the system's re-centering capacity [26]. A hysteretic curve with $\beta = 0$ implies a non-linear elastic behavior and so the system does not dissipate energy and perfectly re-centers (Fig. 1a). Contrarily, values of $\beta > 1$ lead to residual displacements (when the static external force drops to zero they are equal to δ_{res} of Fig. 1c) but also to higher values of energy dissipation. The upper limit of $\beta = 2$ means that there is no active re-centering force applied and the dissipative capacity of the system is maximized. It is so evident that, also for this device typology, the presence of the re-centering force reduces the energy dissipation capacity and the design of retrofit interventions shall result in a compromise between the energy dissipation and the re-centering capability.

The present paper studies the effects on the global seismic behavior of the retrofitting of an existing industrial steel building adopting the steel self-centering device (SSCD) developed in [30]. A parametric analysis is carried out to highlight the influence of the several parameters that defines the device's hysteretic cycle on the global behavior of the structure. The performances of the structure (in the current state and on the retrofitted ones) are evaluated mainly through three parameters: the maximum displacements, the residual ones, the seismic energy components adsorbed by the structure.

The results obtained highlight the effectiveness of the SSCDs in improving the seismic performances of the building and in increasing its resilience by the minimization of the residual displacements.

2. Case study description: modelling, analysis and seismic vulnerability

The building analyzed within this work (see Fig. 2) is characterized by a large mass placed at high altitude and different typologies of horizontal forces resisting systems. It has the function of filtering the gasses coming from the steelwork and can be schematized as made up of a supporting structure, the silos containing the filtered material and the roof.

The building has a regular plan, with overall dimensions 37.80 m × 16.94 m and total height 29.64 m. The supporting structure, with a total height of about 10.80 m, has six bays in the longitudinal (X) direction and three in the transversal (Y) one. As is typical of industrial buildings, where the functionality issues often prevaricate the rules for an optimized structural design, different horizontal resisting systems (Fig. 3) can be individuated such as moment resisting frames (X direction - ground floor), inverted V bracings (Y direction - ground floor) and diagonal bracings (X and Y directions - first floor).

The silos are realized with thin (4 mm) walls stiffened with a close series of horizontal UPN and vertical HEA profiles. The total mass of the silo (23,700 kN), considering the structural elements and the infill material, represents the 86% of the total mass (27,650 kN).

The roof is connected directly to the filter walls and its contribution is considered only in terms of vertical load and mass.

2.1. Linear and non-linear modelling

A preliminary comparison between a full-comprehensive linear model (Fig. 4a) and a geometrically-simplified (Fig. 5) model was carried out given the need to simplify the structural scheme to obtain a reliable and time-saving nonlinear model. The infill material was modelled as five different lumped masses connected to the silo wall by elastic springs (Fig. 4b), whose stiffness was evaluated on the base of the edometric modulus of the infill material.

The "complete" linear model highlighted a structural behavior similar to that of a single degree of freedom, where the great part of the displacement demand is located in the supporting structure. The silos and the roof acted as a rigid body and the resultant stresses were far below the yielding or buckling threshold. It was therefore assumed that the structural behavior could be represented by the simplified model shown in Fig. 5, where the roof was considered simply as dead load and mass, while the silos were substituted by an elastic trusses system, whose characteristics were evaluated to obtain the same first period and modal shape of the "complete" model.

In the simplified model, used to perform nonlinear analyses, each frame was modelled, in OpenSEES [31] using fiber elements and the material was assumed to be elasto-plastic, see Fig. 6b and c.

The nonlinear behavior in shear of the structural elements was not directly considered and only the elastic deformability was taken into account. To check the goodness of such modelling approach, an automatic procedure for the assessment of the elastic behavior in shear was used, checking at the end of each nonlinear analysis that all the structural

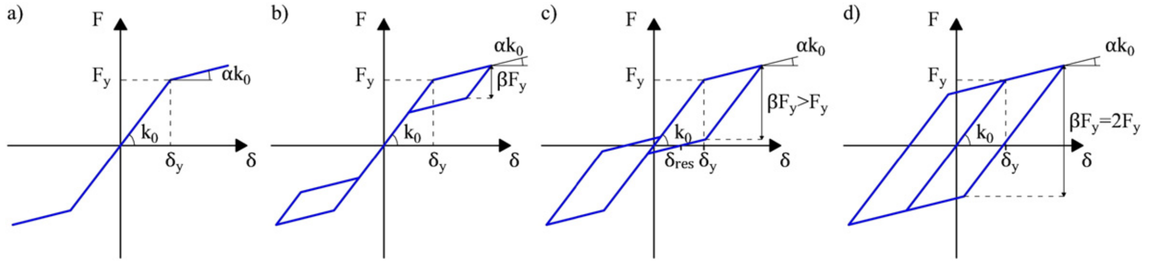

Fig. 1. Idealized flag-shaped hysteretic curve: a) $\beta = 0$ (no dissipation), b) $0 < \beta < 1$; c) $1 < \beta < 2$; and d) $\beta = 2$.