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SEISMIC DEVICES FOR STEEL STORAGE STRUCTURES

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Abstract. *The importance of the logistics sector has increased even more in the last year, due to the Pandemic event which lead to an increasing of the online purchases. Goods and products are generally located in steel frames known as steel racks or simply racks. Consequently also the safe design of these structures, i.e. preserve their fully functionality and avoid their collapse, is becoming of paramount importance, especially when they are located in strong and moderate seismic zones. Despite pallet rack provisions for seismic loads have been significantly improved in the recent years, only two classic ways to enhance the seismic performance are considered: rack netting and structural strengthening. Both of these suggested solutions are not fully effective to preserve the integrity of the stored products that, when subjected to strong accelerations, can topple and fall down. The only reliable and effective systems seem to be the introduction of seismic devices, such as base-isolation and energy dissipation systems. Since no indications about these techniques are reported in the standards, many researches worldwide are trying to fill this gap. Unfortunately, up to now, just theoretical studies and very limited applications are available in literature. In the present paper a short overview on the base isolation systems available on the market for different steel storage rack typologies is presented highlighting main advantages and defects of each solution.*

Keywords: Steel Structures, Adjustable Pallet Racks, Seismic Standards, Eurocode

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1 SEISMIC FEATURES OF PALLET RACKING SYSTEMS

Storage racking systems are engineered structures which are designed to withstand high loads during their life. In many countries all over the world, performance requirements and compliant criteria are established either by law or by technical recommendations, which often regard seismic actions as well. Typical rack frames (Figure 1) are made by open cold-formed thin-walled steel members, which lead to significant and non-negligible torsional effects. In fact, designers must be able to account for the calculation of *bimoment distribution* along the members and the associated tangential and normal warping stress during the design of rack frames [1]. In addition, these members are often prone to local and/or distortional buckling phenomena, which largely precede the attainment of the yielding capacity. These profiles do not guarantee the exploitation of the plastic capacities of the cross sections [2]. For this reason, designers cannot rely on the capacity design principles [3] enforced by the mainstream codes worldwide [4, 5]. For the plastic design of such structures, it is important to rely exclusively on the post-yielding capacity of connections. The cyclic response of standard beam-to-column rack joints is remarked by a strong pinched behaviour. The typical relationship between the bending moment and the relative upright-beam rotation shows a considerable loss of stiffness after the first cycle [6, 7, 8]. Also the connections between uprights and building slab are characterised by a very limited degree of flexural stiffness and bending resistance. In most of the cases, when the cross-aisle direction is considered, the seismic action can pose a risk for the overturning, which becomes the most dangerous limit state. Nevertheless, as happened for the beam-to-column connections, the nonlinear cyclic behaviour can provide a non-negligible ductility to the structure. The main peculiarity of these structures is the quite limited self-weight, which is generally not greater than 5% of the payload. This characteristic brings to periods of vibration which are greatly dependent on the considered level of occupancy, affecting hence either the seismic effects and the structural responses. The design is governed by different load conditions: i) the fully loaded rack (100% occupancy); ii) only the top storage level fully occupied and iii) occupancy levels from 50% to 70% of the total load. These conditions are prescribed in both the static (EN15512:2021 [9]) and the seismic (EN16681 [10]) design codes.

For seismic design purposes, racks are often broken down into two planar lateral resisting sub-systems, which can be used to assess the overall performance of the structure. The down-aisle structural scheme can be studied as a moment-resisting frames; they are made up of uprights (vertical elements) that are connected to pallet-beams (horizontal elements) by means of special beam-end connectors. A great body of research focused on studying its performance by exploiting the analogues techniques used for standard buildings [12]. Down-aisle frames have fundamental periods usually longer than 2.00 seconds (see, [11]), which entails a higher demand in terms of displacement.

The cross-aisle structural scheme is often truss-like and tends to have fewer internal degrees of freedom, thus making fragile collapse modes most likely. Hence, as also shown by many works [13, 14, 15]. Hence, its lateral resistance is promoted by the flexural behaviour of the base-plate connections and the stiffness of the braces. Nevertheless, this scheme gives to the upright frames a high degree of stiffness, which may cause excessive accelerations at decks level. This last circumstance sets the stage for the sliding of pallets on the supporting beams, which can lead to shedding of goods, endangering the health of workers/customers or damage some structural parts and thus likely triggering cascading effects. In the cross-aisle direction, the fundamental period is generally short, comprised between 0.5s and 1.0s [16, 17], placing the structure in the most energetic part of the commonly defined design spectra.

Figure 1: Typical steel storage pallet rack and its main components [11]

Despite the great efforts made to develop more safe and update standards [10], there are issues which still remain not solved. In particular, during a seismic events pallets can overturn and impact against the steel structural skeleton frame causing the well-known *domino effects*, i.e. the progressive collapse of the entire structural system, as showed in 2. An adequate isolation system could be useful to prevent also this phenomena.

Figure 2: Collapse of a warehouse after an earthquake in Italy [18]

2 SEISMIC ISOLATION AND ENERGY DISSIPATION DEVICES

Nowadays, a large variety of devices and techniques are available for seismic isolation of structures, often increasing in its use in highly exposed seismic areas [19], where seismic design of structures can be challenging when post-earthquake functionality is considered [20]. Base isolation systems (BIS) are known to be the most cost-effective and efficient devices for earthquake mitigation [21]. In general, BIS introduces a layer between structures and foundations (or bases) consisting of suitable devices with low lateral stiffness, which almost completely retain the previous vertical stiffness. The main effect of inserting the isolation system is a major shift in the fundamental vibration period of the structure that can be selected to be quite distinct from the energy contents of most predicted seismic events.

Similar benefits are demonstrated when the BIS technique is applied to racking systems. The research proposed by [22, 23] shows that if a warehouse is treated as a standard building, several advantages can be obtained when the seismic performance is evaluated. In particular, the proposed solution concerned the application of elastomeric seismic isolators at the base of the huge warehouse, under the concrete slab, as can be done in traditional buildings. Authors demonstrated a non-negligible benefits especially in terms of reduction of relative displacements and torsional effects. However, despite this approach is promising, it is not always applicable, and its convenience may stuck to only one structural direction due to a quite remarkable difference in periods. For this reason some pieces of research focused on proposing purposely developed hardware to be used for rack systems.

2.1 Seismic isolators for cross-aisle direction

2.1.1 Pellegrino® isolation system

The trademark Pellegrino® identifies a system that provides seismic isolation along the cross-aisle direction alone to pallet type steel storage racks, by incorporating high damped elastomeric bearings and friction plates (Figure 3). Filiatrault et al. (2008) [24] presents a summary of the experimental results of isolated pallet racking tests performed on the triaxial shake table at the University of Buffalo (USA). The proposed Pellegrino® isolation system works in the cross-aisle direction and can cut down the amount of energy that is transmitted to the superstructure, thus reducing the likelihood of content spillage. Figure 3 shows a detailed view of the system, which consists of a *U-shape* plate (*Horizontal Support*), inserted inside a steel box (*Box Fabrication*) which is welded on the base plate (*Base Plate*). For the sake of brevity more details are not reported here. The base plate must be anchored to a rigid slab by means of anchor bolts. The results obtained from full-scale experimental tests [24] showed: i) the system reduce greatly the top accelerations in the cross-aisle direction but it has also some beneficial effects in reducing the accelerations in the down-aisle direction. The efficiency of the base isolation system in reducing the cross- and down-aisle accelerations increases with the weight of the merchandise. This beneficial effect is directly related to the changing in the fundamental period of vibration which increase in both directions with respect to the natural period of the racks with fixed bases; ii) damage on the uprights and merchandised overturning, which characterised the fixed base tests, have never observed in the base isolated cases; iv) the system brings to a great reduction of the interstorey drifts.

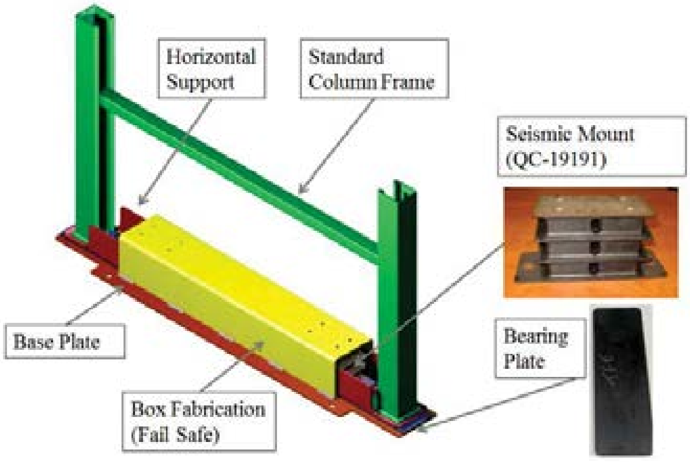

Figure 3: device installed under a single-entry pallet rack, render of Pellegrino®system (font https://www.ridgurak.com/)

2.1.2 IsolGOODS® isolation system

FIP MEC has developed a quite novel device (Figure 4) that is an unidirectional seismic isolation device that provides seismic isolation to the rack in the cross-aisle direction only. This solution is effective because the fundamental period of racks in the cross-aisle direction is usually short, and thus the isolation system can provides a greater shift in period while keeping a small footprint. This allows to use the pallets slots at ground level, as in a conventional pallet rack, while part of said pallet slots is lost when using multi-directional isolators. Additionally, the system is able to prevent the up-lift of the rack, that could happen in particular load cases under high seismicity actions, in particular in single-entry pallet racks. IsolGOODS® is classified as a pendulum isolator or Curved Surface Slider (CSS), as defined in [25], with a single surface of sliding. Low-lateral flexibility is guaranteed by a low-friction material, and FIP MEC uses a particular material for this device, i.e. FIP friction material (FFM), which ensures very high load-bearing capacity and wear resistance [26]. The performance of the IsolGOODS® device has been assessed by means of shake table test performed at the FIP Laboratory Tests (Italy). A one-bay four-storey pallet rack was equipped with the presented isolation system and its dynamic behaviour was studied under a set of ground motions, as discussed in Tagliafierro et al. (2021) [17].

Figure 4: device installed under a single-entry pallet rack: render view of IsolGOODS®solutions [11]

Together with the two presented solutions, other special devices have been developed by different company during the last years for storage racks, like the LOKI system one (http://www.lokibase.com, accessed 2021). However, up to now, there are no scientific results published on international journals for this or other systems.

2.2 Energy dissipation

For the points introduced in the previous section, the common procedures enforced by many codes for the seismic design of structures associate a certain structure ductility to a certain degree of energy dissipation. The most common approach foresees the use of a factor used to scale down the seismic demand, by inherently assuming that part of the energy that an earthquake can possibly transmit to a structure is partially dissipated/avoided. In general, a dissipative structure can be designed by either locating ductile zones or adding extra devices to perform that duty. The latter represents the approach that should be followed for inherently fragile structures.

2.2.1 Uplifitng and sliding friction base-plates

The considered device was proposed as a friction-based devices and can provide energy-dissipation by means of wide and stable loops, with a negligible hardening phenomenon and experiencing no damage. For seismic resistant structures, purposely designed devices are commonly embedded into braces [27], beam-to-column joints, and into column-base joints [28], whereas it is always important to guarantee an even distribution of inter-storey drifts to exploit the displacement-dependent energy dissipation of these devices [29]. A novel dissipation joint was studied by Tang et al. (2017) [30] for adjustable pallet racking systems. It was developed for low and medium-rise racks, and the method consists of inserting a steel sliding friction base-plate connected to all the uprights (Figure 5(a)). The device, presented for the first time in Clifton (2005) [31] (Figure 5(d)), can dissipate energy thanks to a friction-based mechanism rather than forming yielding zones at the base connections. On top of this, this device promotes a rocking behaviour, so that, when the device is activated, the structure benefits from a further shift in period.

2.3 Seismic performance of Grana cheese steel racks

As it is well-known, Grana is a type of Italian cheese proposed in the form of large wheels. Generally Parmigiano cheese is stored in structures made by composed steel tubular columns (two tubes of 50 $\times$ 50 mm with thickness of 3 or 4 mm and a global height from 7 to 9 m) having 1.5 m of span (Figure 6). Along the cross-aisle direction, each bay is connected by means of wooden panels, on which the cheese wheels rely, and via a continuous tubular steel on the top. Global length can vary from 18 to 40 m. When the steel rack is connected to the concrete wall (case S2 of Figure 6), it is simply supported on the floor, i.e. no anchors are present. On the other hand, when it is anchored to the floor, it is not connected to counter walls (case S1 of 6). Bracings are always present only in the down-aisle direction. A great number of these structures have been designed more than 20 years ago, considering only vertical forces (with no seismic actions) and, therefore, they are generally in an unsafe condition. For this reason, earthquakes occurred in May 2012 in Emilia Romagna (Italy) caused causes severe damages to grana warehouses, that progressively collapsed causing a domino effect leading to the loss/depreciation of several thousands of tons of grana cheese.

After this catastrophic event more attention has been paid to the seismic behaviour of these structures. Franco et al. [32] proposed a complete study on the dynamic behaviour of these racks, focusing the attention on the seismic improvement techniques. A solution proposed

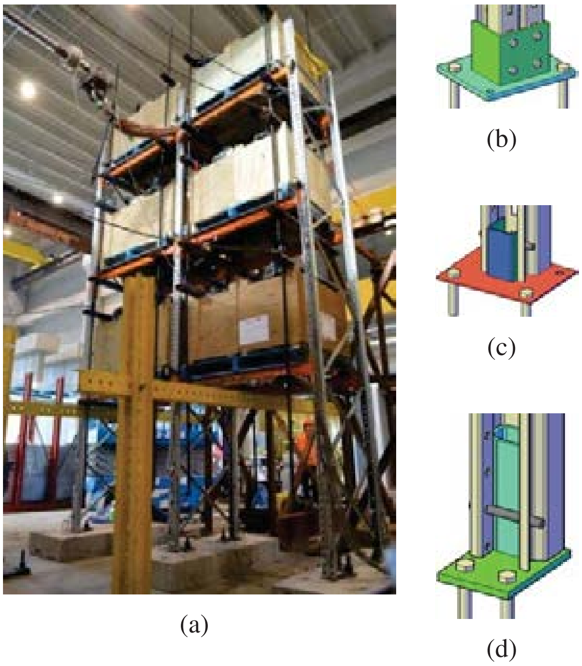

Figure 5: (a) Test setup of the fully loaded frame [30]; sketches of the three connections compared: (b) rigid base-plate, (c) yielding base-plate and (d) friction base-plate

by the Authors is to use a passive-control system: viscous dampers are directly connect to the surrounding concrete structures (see, S3 of Figure 6). The time-history analyses of the proposed configurations have shown that the use of dampers presents noteworthy advantages for all cases in which the constraint degree of the racks is augmented and, consequently, their stiffness is increased. The advantages are in terms of stress reduction in the rack elements, and of reaction forces transmitted to the surrounding support structures.

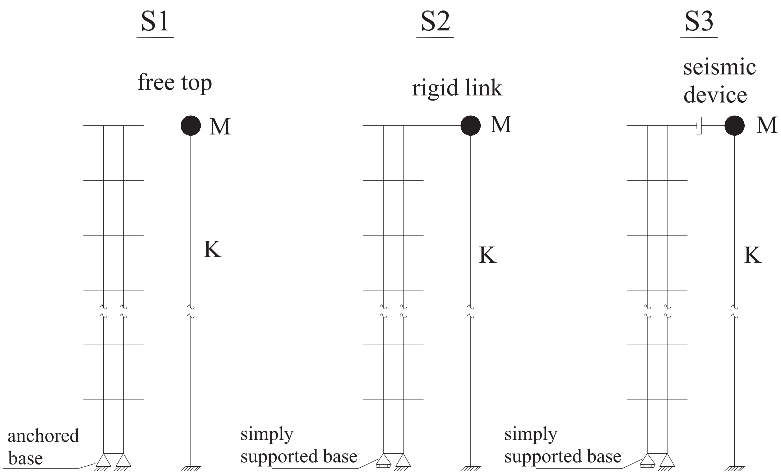

Figure 6: Three structural configurations that can be considered to simulate the *scalere* in the cross-aisle direction (after Franco et al [32]).

Furthermore, as discussed in [33], some producers, instead of performing specific seismic study on their warehouse, decided to renew completely the steel structures by changing completely the structural system. The brand new structures that store Grana cheese consist of cold-formed columns; the components of the bracing system are made using structural bolts, instead of welding. Boxed composite columns (different from producer to producer) are realised by coupling two open cold-formed mono-symmetric channels or sigma members. Along the columns height (in general about 7-9 m), horizontal L-profiles (angles) are connected, vertically spaced at about 330 mm and protrude beyond the central column as cantilever beams supporting the wooden boards (with 30 mm thickness), on which cheese wheels are directly located. In the longitudinal (down-aisle) direction, the geometry of the oldest and new type cheese rack is the same, differing only for the structural components and for the connection system between columns. This new frames are never connected to the surrounding concrete structure and in seismic areas, rely completely on the hysteric behaviour of the base-plate.

3 FINAL REMARKS

The deep understanding of the seismic performance of steel structures used to store good and products, known as steel storage pallet racks, is becoming of a paramount importance. In the specific standards only the classic techniques to improve structural behaviour of racks in seismic zones are provided, with no indications about the seismic isolation or energy dissipation devices. If overturning of stored goods is of concern, there are only two ways reported for the improvement of the safety of racks in seismic zones: rack netting and structural strengthening. The rack netting is a steel netting installed on all sides of the rack, covering the bay openings from top to bottom. It can be noted that if netting is installed, it then needs to be removed and reinstalled every time a storage slot is accessed. As regards the latter provision, it can be noted that it allows the structure to meet the code requirements, but increases the stiffness of the structure at the same time, adding rigidity and introducing higher accelerations throughout the system. The two approaches can be used together, but neither rack netting nor structural strengthening protect the rack and prevent adequately the product shedding.

The product shedding prevention must be always considered in the design process, being the total cost of stored goods generally much higher than the cost of the structural components. Seismic isolation seems to be a very useful and effective solution, and a number of investigations are nowadays in progress in many parts of the world. The paper has shortly discussed the main characteristics of several devices applied to different typologies of steel storage racks, by reporting studies taken from the available literature. The two innovative systems called RIGID-U-RAK system (Pellegrino®) and FIP MEC System (IsolGOODS®) are reported showing main characteristic and advantages of each solution. The results show that the application of a seismic isolation system can reduce accelerations on both cross- and down-aisle directions, and avoid the overturning of the stored goods and damage on the uprights. Finally, the use of dissipative devices is discussed. It can be an effective and low-cost solution as demonstrated by Tang et al. (2017) and Franco et al. (2015). Devices of such kinds can provide rack structures with more resilience, for the design and retrofit of structures, as it is shown in the collected research.

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