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An innovative seismic isolation device based on multiple articulated quadrilateral mechanisms: analytical study and shake-table test

Gabriele Guerrini[a,b], Giovanni Ausenda[c], Francesco Graziotti[a,b], Andrea Penna[a,b]
[a] *Department of Civil Engineering and Architecture (DICAr), University of Pavia, Via Ferrata 3, 27100 Pavia, Italy*
[b] *European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Via Ferrata 1, 27100 Pavia, Italy*
[c] *Kyneprox S.r.l., Via Dell'Artigianato 44, 20083 Vigano di Gaggiano, Italy*

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ABSTRACT
Seismic isolation is a topic of great interest in high-seismicity regions worldwide, because it can be applied as an integrated system in new construction, as a retrofit solution for existing buildings, and as a passive protection technique for non-structural components. Several isolation devices are currently available on the market, typically classified into the two families of elastomeric and curved-slider bearings. Despite their undeniable effectiveness in reducing the seismic accelerations transmitted to the isolated structure and to its content, these devices may increase significantly the construction cost of ordinary buildings and may require particular maintenance to preserve a stable performance over time. In order to overcome the disadvantages of initial and maintenance costs, an innovative seismic isolator named "Kinematic Steel Joint (KSJ)" has been patented based on a multiple articulated quadrilateral mechanism. In fact, the proposed device is entirely made of steel components obtained by simply cutting, folding, and pinning metal sheets, eventually employing stainless steel to prevent corrosion issues. The trajectory imposed by the KSJ isolator to the supported mass combines horizontal with increasing vertical displacements, resulting in a pendulum-type motion with self-centering behavior. The friction developing within the pinned joints can be exploited to grant energy dissipation capacity to the device. This paper discusses the kinematic, static, and dynamic response of a prototype of the KSJ isolator, based on analytical and experimental considerations from a shake-table test conducted at the EUCENTRE Foundation (Pavia, Italy) laboratories.

1 INTRODUCTION

Earthquakes induce cyclic lateral accelerations on building structures and contents. The resulting variations of internal forces and deformations can cause progressive damage, eventually up to collapse conditions, if the structure is not properly designed. The current seismic design philosophy is centered on the concept of ductility, i.e. on the ability of structures to deform beyond their elastic limit, accepting the development of significant damage but controlling it to avoid collapse (Guerrini et al., 2015).

However, protecting buildings from earthquakes requires not only to ensure life safety and collapse prevention, but also to limit the economic and social cost of post-event disruption, repair, and reconstruction. For this reason, seismic isolation techniques have been slowly establishing alongside the more traditional ductile design approach over the past few decades. In fact, isolation allows reducing the accelerations transmitted to the building masses, the deformation and ductility demand on structural elements, and the potential damage to structures and other components.

Typically, seismic isolation is provided at the basement level or crawl space of buildings, from which the widespread definition of "base isolation", even though higher locations may be alternatively suitable depending on the building configuration or on which portions require special seismic protection (Kelly, 2001). Isolation acts as a filter for the seismic input transmitted to the superstructure (the entire building or a portion of it) above the isolation layer, reducing the acceleration, displacement, and deformation demand imposed on its elements and on its contents.

Seismic isolation systems (Figure 1) usually include: (i) isolators, characterized by low lateral stiffness, which allow decoupling the ground motion from that of the horizontal rigid diaphragm located at the superstructure base; and (ii) energy dissipators, required if the isolators do not provide enough damping to limit the deformation demand on the isolators themselves (Christopoulos and Filiatrault, 2006). Isolation systems need to recenter to their at-rest position at the end of the seismic excitation; if the isolators cannot ensure this behavior, specific devices can be added to the system for this purpose.

Two families of isolators are currently adopted for buildings (Christopoulos and Filiatrault, 2006): elastomeric bearings and curved-slider or friction pendulum bearings. The cost of these devices can significantly increase the construction cost of ordinary buildings in some cases, making the isolation technology less appealing for their owners. Moreover, they may need specific maintenance or replacement over time, to control elastomer aging, steel corrosion, sliding surface degradation, and other effects that may impair their performance (Lee, 1981; Kauschke and Baigent, 1986; Clark et al., 1996; Morgan et al., 2001; Constantinou et al., 2007). Consequently, access to the isolators must be granted even when they are located within crawl spaces.

To address the issues above, Kyneprox S.r.l. has patented a new type of isolator, consisting of a double articulated quadrilateral with crossing rods entirely made of steel, named “Kinematic Steel Joint (KSJ)”. The device grants a recentering pendulum-type motion to the superstructure, as it associates horizontal with upward displacements. Similarly to friction pendulum isolators, the restoring force is proportional to the slope of the trajectory. The KSJ also provides some energy dissipation, taking advantage of friction within pin connections between rods and plates.

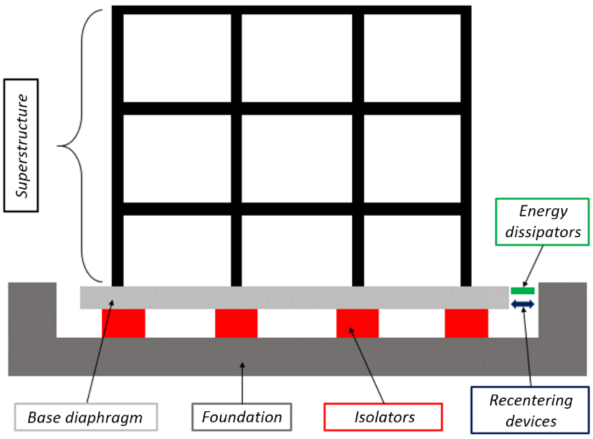

Figure 1. Schematic seismic isolation system.

Compared to commercially available devices, the KSJ promises reduced production costs, because it consists of pinned steel rods and plates obtained by simply cutting and folding metal sheets. Moreover, this device should require lower maintenance costs than conventional isolators, comparable to the ones associated with steel structures or even smaller if stainless steel is used to fabricate its components.

2 GEOMETRIC AND ANALYTICAL CONSIDERATIONS

2.1 Prototype geometry

This paper discusses the behavior of a KSJ prototype (Figure 2), with analytical considerations and experimental validations by shake-table tests. The prototype was made of S235 steel rods and plates, connected by bolts and thrust bearings acting as pins. Stainless steel may be used for practical implementations, to reduce corrosion sensitivity.

Top and bottom square plates, with 10-mm thickness and 400-mm side, allowed connecting the device to the shake-table (foundation) and to the rigid mass (superstructure) by four 16-mm diameter bolts each. Three rows of 10-mm-thick vertical plates, with shape compatible with the pendulum-type motion of the rods and with their maximum rotations, were fillet-welded to the horizontal ones plates.

Figure 2. Kinematic Steel Joint (KSJ) isolator prototype.

Three modules, each consisting of four diagonal rods crossing in pairs and a horizontal rod, were mounted side by side in parallel and pinned to the vertical plates. All rods were obtained from 10-mm-thick steel sheets; notches and chamfers allowed to accommodate the maximum rod rotations corresponding to the displacement capacity of the device.

Finally, a restraining system, consisting of rigid steel plates and cylindrical bearings, forced the device horizontal displacement in a single direction, preventing transverse and torsional deviations. For practical applications, combining in series two devices with orthogonal orientation would allow full 2-dimensional motion in a horizontal plane.

Aligning more than one KSJ isolators, fixed to the shake-table and to the rigid superstructure mass, prevented the rotation of the top horizontal plate and resulted in a single-degree-of-freedom (SDOF) system with pendulum-type motion. The same result can be obtained in applications to buildings, providing sufficient out-of-plane stiffness to the base horizontal diaphragm.

2.2 *Kinematic analysis*

The trajectory imposed by the KSJ isolator to the superstructure was obtained imposing a series of rotations to one of its bottom diagonal rods, while preventing rotations of the top and bottom horizontal plates. Seven configurations were analyzed up to a 12° rotation of the control rod, associating horizontal (x) with vertical (z) displacements. This operation was conducted first considering the vertically unloaded device (Table 1), then assuming a deformed at-rest configuration with a 10-mm downward displacement of the top plate and shortened rods (Table 2), approximately simulating the effect of a 51-kN gravity load.

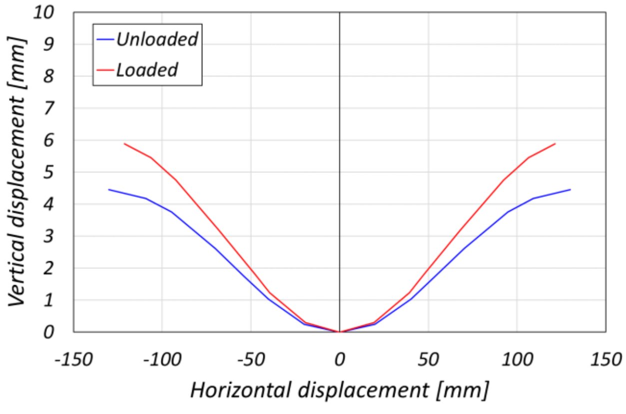

Figure 3. Analytical trajectories of the KSJ prototype.

Table 1. Analytical behavior of an unloaded KSJ prototype.

Rod rotation [°]	Horiz. displ. [mm]	Vert. displ. [mm]	Avg. radius [m]	Avg. period [s]
± 2.5	± 19	0.2	0.78	1.77
± 5	± 40	1.0	0.79	1.78
± 6	± 54	1.7	0.83	1.83
± 8	± 70	2.6	0.94	1.94
± 10	± 94	3.7	1.20	2.20
± 11	± 109	4.1	1.43	2.40
± 12	± 130	4.4	1.90	2.77

Table 2. Analytical behavior of a loaded KSJ prototype.

Rod rotation [°]	Horiz. displ. [mm]	Vert. displ. [mm]	Avg. radius [m]	Avg. period [s]
2.5	±19	0.3	0.62	1.58
5.0	±39	1.2	0.63	1.59
6.0	±47	1.7	0.63	1.59
8.0	±68	3.1	0.73	1.71
10	±92	4.7	0.90	1.90
11	±106	5.4	1.04	2.05
12	±121	5.8	1.25	2.24

Figure 3 displays the analytical trajectories z(x) obtained for the two cases. Initially the trajectories are concave up; then, an inflection point is located at horizontal displacements of 50 mm to 60 mm, and the concavity is reversed downward up to the ultimate displacement capacity.

Figure 3, Table 1, and Table 2 show that the geometric variations due to gravity loading affect the lateral behaviour of the KSJ isolator. More specifically, the maximum horizontal displacement (corresponding to a rod rotation of 12°) slightly reduces from ±130 mm to ±121 mm, while the trajectory becomes steeper: in fact, the same horizontal displacements are reached with larger upward displacements.

2.3 *Static analysis*

The lateral force-displacement relationship of the isolator can be derived once its trajectory is known. The force required to move the device includes a restoring component, F_R, and a friction component, F_F. They can be calculated from the analogy, at any given point, between the motion of a pendulum of mass M and weight $W = M\,g$, and the one of the same weight on an inclined plane, with slope $\tan\alpha$ equal to the slope of the trajectory dz/dx at that point.

The restoring force is given by the slope of the trajectory. If the function $z(x)$ describes the trajectory, then the restoring force is given by:

$$F_R = W \cdot \tan\alpha = W \cdot \frac{dz}{dx} = M \cdot g \cdot \frac{dz}{dx} \qquad (1)$$

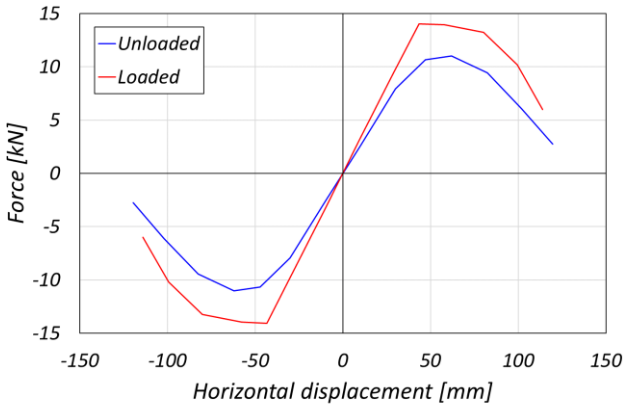

Figure 4. Analytical force-displacement relationships of the KSJ prototype.

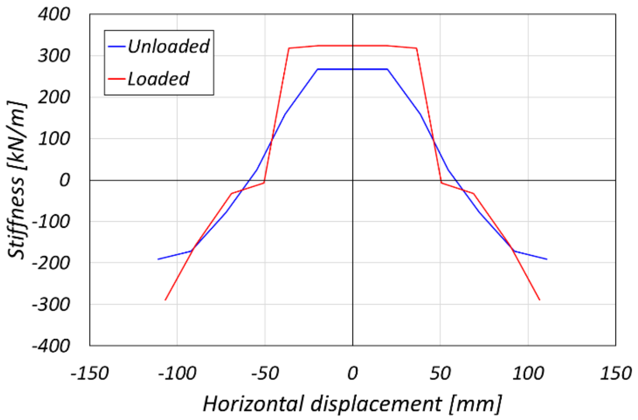

Figure 5. Analytical stiffness-displacement relationships of the KSJ prototype.

The equivalent stiffness of the device, which varies along the trajectory, can be evaluated by taking the derivative of the restoring force with respect to the horizontal displacement:

$$K = \frac{dF_R}{dx} = W \cdot \frac{d^2 z}{dx^2} \cong \frac{W}{R_0(x)} = \frac{M \cdot g}{R_0(x)} \quad (2)$$

where $R_0(x)$ is the radius of curvature of the trajectory at the specific point, approximately equal to the second derivative of the trajectory if this is sufficiently flat. The initial deformation due to vertical loads increases the lateral stiffness and strength offered by the isolator.
Figure 4 and Figure 5 plot the relationships $F_R(x)$ and $K(x)$, respectively, for the KSJ prototype. A total weight W = 205 kN was considered, consistently with the shake-table test setup that included four in-parallel KSJ isolators, supporting 51 kN each. In both cases of gravity-unloaded and loaded device, the stiffness becomes zero in correspondence of the inflection point of the trajectory at lateral displacements of about 50 mm to 60 mm, where the curvature is also zero. The initial vertical deformation imposed by the vertical load results in an increased lateral stiffness and strength, associated with a steeper trajectory as observed from Figure 3.

The friction component can be obtained from similar considerations, projecting the frictional resistance parallel to the trajectory slope (or to the inclined plane) in the horizontal direction. It can be shown that the resulting friction component is independent of the trajectory, and is related to the weight and the friction coefficient μ of the pinned connections only:

$$F_A = \mu \cdot (W \cos\alpha + F_R \sin\alpha) \cos\alpha = \mu \cdot W \quad (3)$$

2.4 Dynamic analysis

The trajectory of the KSJ isolator is characterized by varying curvature, which means also varying radius of curvature point by point. The average radius R for a given lateral displacement along the trajectory is evaluated for the circle through the at-rest position and through the symmetrical points at the positive and negative displacement of interest. The average period T_b of the isolated system (assumed rigid) can be obtained in terms of average radius R as for a simple pendulum, independently of the mass:

$$T_b = 2\pi \sqrt{\frac{R}{g}} \quad (4)$$

Table 1and Table 2 list the values of R and T_b for the seven displaced positions analyzed. The initial vertical deformation due to a 51-kN gravity load causes the period to shorten, as the isolator offers a stiffer response compared to the unloaded case: the average radius at maximum displacement reduces from 1.90 m to 1.25 m, while the period shortens from 2.77 s to 2.24 s. It can be observed that T varies between 1.58 s (small lateral displacement, loaded device) and 2.77 s (maximum lateral displacement, unloaded device).

3 DYNAMIC SHAKE-TABLE TEST

3.1 Test setup

A unidirectional (North-South) dynamic shake-table test was conducted at the 6DLab of the EUCENTRE Foundation in Pavia, Italy, to investigate the behavior of the KSJ prototype experimentally. The setup included four in-parallel devices, supporting a mass with a total weight of 205 kN (Figure 6). The mass consisted mainly of a reinforced concrete prismatic block, weighting 158 kN, resting above two longitudinal HE 400 B steel beams (10.1 kN each), which in turn were supported by two KSJ isolators each.

Figure 6. Shake-table test setup.

Additional masses were provided by four steel adaptor plates connecting isolators and beams (0.4 kN each), and by non-structural elements such as two clay vases (negligible mass) supported on two concrete blocks (2.3 kN each), four marble blocks to simulate statues and other rocking components (18.6 kN total), and a museum showcase (2.5 kN) with a small-scale, 3D-printed replica of Michelangelo's David (negligible mass).

Two steel guides were mounted below the longitudinal beams to prevent transverse (East-West) and torsional motion, should the out-of-plane restraints of the devices have failed. Two safety steel braces were provided to stop the mass in case of failure of the KSJ devices or of their connections, after reaching the maximum longitudinal displacement capacity.

Before the dynamic testing sequence, a quasi-static test was conducted to assess the force-displacement relationship of the setup. The same setup was used, with only one difference: during this phase, the mass was tied to the laboratory strong-floor by a steel cable with a load cell and a turnbuckle (visible in Figure 6), which were then removed to proceed with the dynamic protocol. A dynamic fixed-base test was also performed by fastening the concrete mass to the steel braces, to evaluate the response of the non-structural components in this condition. These two tests will not further discussed in this paper.

3.2 *Instrumentation*

The specimen was instrumented with accelerometers, potentiometers, and wire potentiometers. Among others, one tri-axial accelerometer was mounted at the center of the shake-table platen, and two tri-axial accelerometers were provided at the East and West sides of the reinforced concrete block (visible in the bottom photo of Figure 6). The inertial force of the system was determined by associating 50% of the total mass with each accelerometer on the block.

Potentiometers were used to record the motion of the isolators and wire potentiometers to measure the displacements of the non-structural elements. In particular, each KSJ device was monitored by three potentiometers along three orthogonal directions (Figure 7): two of them were necessary to recover the pendulum-type trajectory within the vertical plane, while the third one allowed verifying the efficiency of the out-of-plane restraint at preventing transverse displacements. A pair of potentiometers was also employed to check that no sliding occurred between reinforced concrete block and steel beams.


Figure 7. Potentiometers monitoring a KSJ prototype.

Table 3. Input signal characteristics.

Parameter	EMN025	CIN030
Date	29/05/2012	30/10/2016
Time	06:40:18	07:00:02
Moment magnitude	6.0	6.5
Province	Modena	Perugia
Municipality	Finale Emilia	Preci
Latitude [°]	44.8486	42.8793
Longitude [°]	11.2479	13.0334
Rupture distance [km]	6.68	8.95
Component	Nord	Nord
PGA [g]	0.254	0.310

3.3 Test protocol

The dynamic test was conducted applying two natural seismicity ground motion records to the shake-table in the North-South direction. Each signal was applied scaling its amplitude at 25%, 50%, 75%, 100%, 125%, 150%, 175%, 200%, and 250%, creating two incremental sequences. The records were downloaded from the Italian database ITACA (ITalian ACcelerometric Archive; Luzi et al., 2019), provided by the National Institute of Geophysics and Volcanology.

The first ground motion signal, labeled EMN025, was recorded during the 2012 Northern Italy earthquake sequence; the second one, abbreviated CIN030, during the 2016 Central Italy seismic events. More details can be found in Table 3. In the next paragraphs, each step of the incremental dynamic test will be identified by the three letters of the signal label, followed by the percentage of amplitude scaling. In particular, the discussion will focus on EMN250% and CIN250%, i.e. the 250%-scaled runs with both input signals.

3.4 Test results

The shake-table test results are discussed in terms of: (i) trajectories recorded for each isolator; (ii) hysteretic response of the complete dynamic setup; and (iii) effectiveness of the isolation system at reducing the seismic demand on SDOF oscillators.

3.4.1 Isolator trajectories

Figure 8 and Figure 9 show the trajectories recorded for each of the four KSJ isolators during the highest amplitude runs with the two input signals. A pendulum-type motion with variable curvature can be observed. For isolators no. 3 and 4 the trajectory is slightly shifted to the left, probably due to some misalignment during assemblage of the setup which caused these devices not to start exactly from their at-rest position.

Good agreement can be observed between analytical and experimental trajectories. The maximum horizontal displacement of about 80 mm corresponds to an upward displacement of nearly 4 mm on isolators no. 1 and 2 (those starting from at-rest position), as correctly predicted by the kinematic analysis under gravity load.

An additional effect not caught by the analytical model is the isolator vertical (downward) settlement, which progressively cumulated up to residual values ranging between 0.2 mm and 0.4 mm after EMN250%. This effect showed a stabilizing tendency, with residual settlements varying between 0.2 mm and 0.6 mm at the end of CIN250%. These vertical displacements can be attributed to plays and adjustments of the pinned connections.

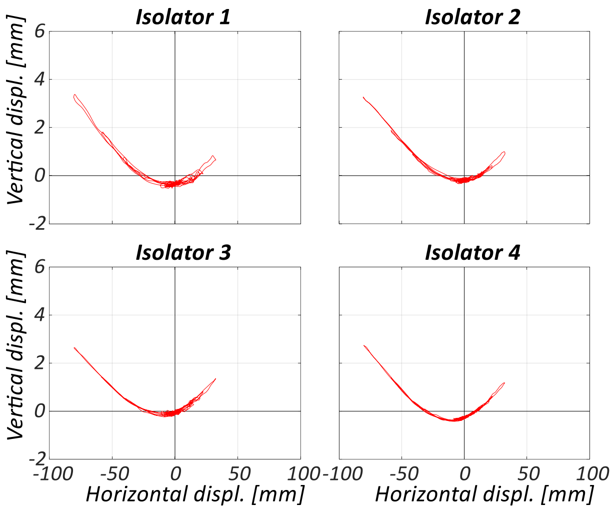

Figure 8. Isolator trajectories under EMN250%.

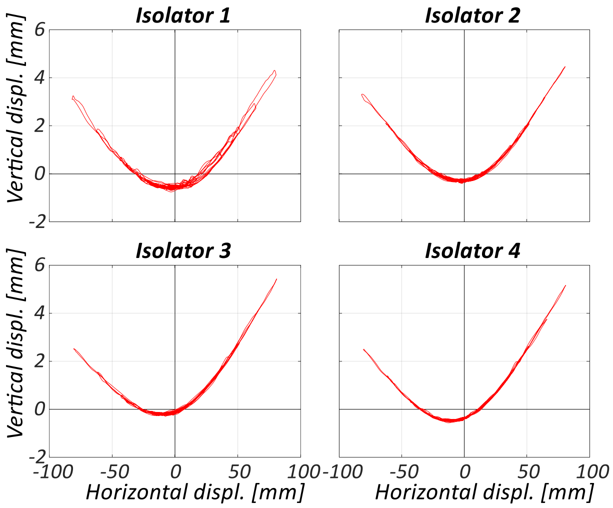

Figure 9. Isolator trajectories under CIN250%.

3.4.2 Overall hysteretic responses

Figure 10 and Figure 11 illustrate the hysteretic lateral force-displacement response obtained for the entire system during runs EMN250% and CIN250%, respectively. The loops resemble those obtained for friction-pendulum devices, except for their variable slope due to the KSJ variable-curvature trajectory.

The loop width measured along the force (vertical) direction represents the effects of friction at the pinned joints. In particular, a width of about 12 kN indicates a friction force of approximately 6 kN. If the friction effects are subtracted from the loops, the experimental results confirm the analytical prediction, with a restoring force of about 15 kN for 80 mm of maximum lateral displacement. Moreover, the loop tangent becomes horizontal (zero equivalent stiffness) at a lateral displacement of about 60 mm, where the trajectories of Figure 8 and Figure 9 approach straight lines (zero curvature), in accordance with the analytical model.

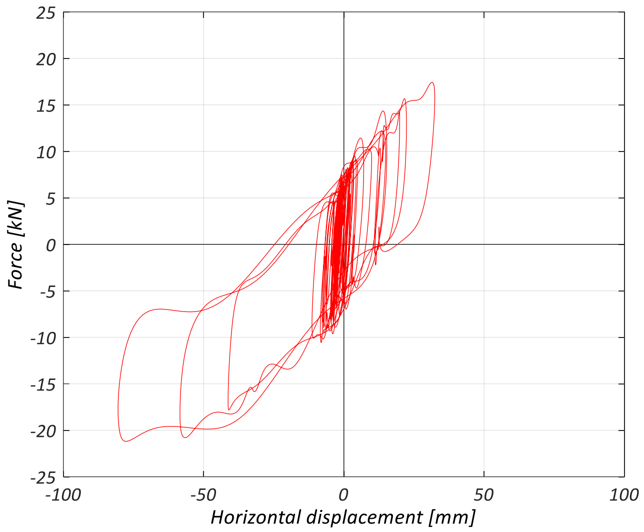

Figure 10. Overall hysteretic responses under EMN250%.

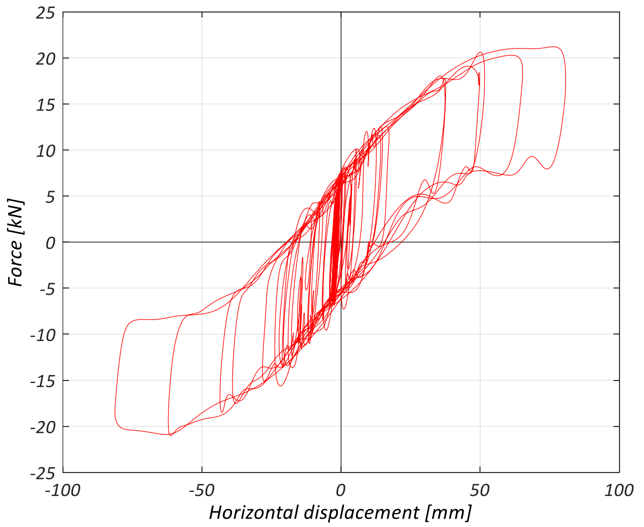

Figure 11. Overall hysteretic responses under CIN250%.

3.4.3 Isolation effectiveness

The effectiveness of the seismic isolation technique was evaluated in terms of elastic response spectra at 5% viscous damping ratio. The spectra were calculated for the signal recorded by the accelerometer placed on the shake-table, and for the average time-history recorded by the two accelerometers attached to the reinforced concrete isolated mass. They represent the demand on SDOF oscillators equivalent to the superstructure, directly supported on the ground or isolated by the KSJ devices. The ratio of the two spectra informs about the effect of the isolation system at reducing (or magnifying) the demand, depending on the period of the oscillator.

Figure 12 and Figure 13 show that for both input signals scaled at 250% of their amplitude the isolators reduce the spectral ordinates up to periods of about 1.0 s. Instead, for longer-period oscillators the demand is amplified by the introduction of the devices: the maximum amplification can be found at periods of 1.5 s to 1.7 s. Considering a maximum displacement of 80 mm, the average period was consistently predicted as $T_b \approx 1.8$ s (see Table 2). According to the recommendations of the Italian building code (MIT, 2019), this isolation system could be adopted for structures with fundamental period $T_s \leq 0.33\ T_b = 0.6$ s, which would fall within the spectral-reduction range.

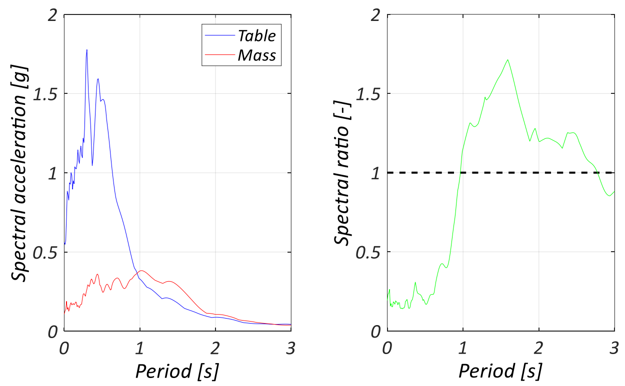

Figure 12. Isolation effectiveness under EMN250%.

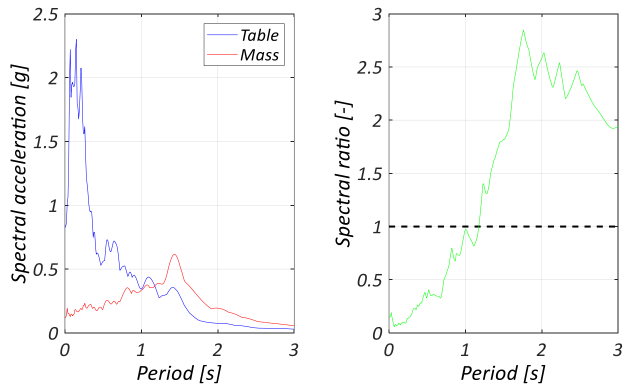

Figure 13. Isolation effectiveness under CIN250%.

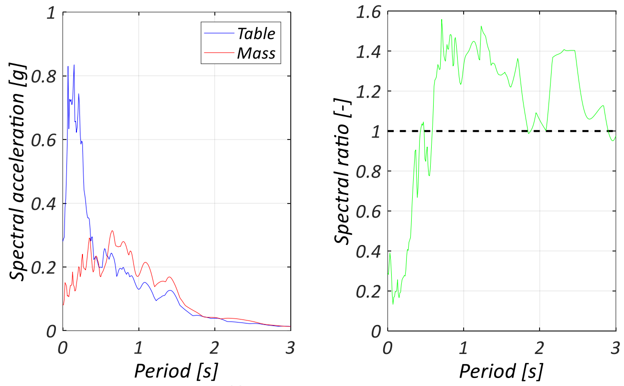

Figure 14. Isolation effectiveness under CIN100%.

It is important to notice that the average period of the isolation system depends on the lateral displacement underwent by the KSJ devices: shorter isolation periods are associated with smaller displacements (see Table 2). In fact, also the amplitude of the spectral-reduction period range depends on the displacement demand on the KSJ isolators: for lower-intensity input motions, which impose smaller displacements on the isolators, the range becomes narrower. For example, Figure 14 shows that the spectral-reduction range under CIN100% is limited to a maximum of 0.4 s.

4 CONCLUSIONS

This paper has discussed the analytical and experimental response of an innovative seismic isolation device based on a multiple articulated quadrilateral mechanism, named “Kinematic Steel Joint (KSJ)”. Compared to the isolators currently available on the market, the KSJ solution offers the advantages of competitive fabrication costs, because it consists of simply cut and folded steel sheets with pinned joints, and low-maintenance requirements, if it is made of stainless steel.

An analytical study revealed that the KSJ isolator applies to the isolated superstructure a restoring force proportional to the slope of the motion trajectory, consisting of upward and lateral displacements with recentering features, similarly to friction pendulum devices. The period of the isolated system is independent of the mass and is related to the curvature of the trajectory, which is not constant. However, an average period can be estimated with the equation of a simple gravity pendulum, considering an average radius of curvature at the lateral displacement of interest.

The results of an incremental dynamic shake-table test campaign confirmed the analytically predicted behavior. Moreover, the KSJ solution proved to be effective at reducing the seismic demand on SDOF oscillators representative of the superstructure, in terms of elastic response spectra. The period range of isolation effectiveness varies with the displacement demand imposed on the isolators and on the corresponding average period. If the superstructure fundamental period approaches or exceeds the average period of the isolation system, amplification effects may occur instead. Finally, the KSJ isolators can provide some energy dissipation thanks to friction at the pinned joints.

The results of this preliminary study promise a positive performance of the KSJ devices. Further investigations and geometric optimizations will allow to reduce the size of the isolators and to obtain lateral displacement ranges and trajectory curvatures compatible with a variety of building isolation configurations.

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