VIBRATION CONTROL OF AN INDUSTRIAL COMPOSITE SLAB SUBJECTED TO IMPACT LOADS AND IMPROVEMENT OF THE OVERALL BUILDING SEISMIC PERFORMANCE USING TOGGLE-BRACE DAMPERS

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1. ABSTRACT

This paper presents the preliminary findings of a case study, undertaken for enhancing the vibration performance of an industrial two-way composite slab subjected to impact loads as well as for the seismic retrofitting of the entire building. Struts as well as toggle-brace-damper configurations have been effectively combined to achieve the aforementioned two-fold goal. With respect to the vibration control of the slab, provided that the availability of the field measurements was not enough to undertake a full forensic engineering study, the proposed strengthening scheme in both directions was selected so as the resulting system fundamental frequency (i.e. beam and girder combined mode) would lie well above the minimum recommended values. Furthermore, in the girder direction, these struts were aligned in a toggle-brace-damper configuration in order to: (a) Employ shallow trusses, due to operation-related restrictions, while (b) magnifying the vertical slab displacements associated with the impact load and (c) the horizontal deformations imparted by seismic loads to this stiff building so that the dampers experience increased velocities and maximize their effectiveness at both the serviceability and the ultimate limit-state.

2. INTRODUCTION

This paper presents the preliminary findings of a case study that was undertaken on an industrial steel structure to (a) mitigate the unwanted floor vibrations of a two-way composite slab and (b) retrofit the entire building to enhance its seismic performance. The source of floor vibrations is the motion of heavy vehicles (e.g. forklift) that contain no actual suspension, compared to a typical car, thus providing what is essentially a near-impact loading to the long and flexible floor slabs of the building. In terms of its seismic performance, the proposed retrofitting scheme aims at offering a practicable and costeffective solution for meeting high performance requirements, equivalent to remaining operational at rare seismic events and receiving controlled moderate damage at very rare ones.

3. BUILDING DESCRIPTION

The building is a 2-story steel structure with a rectangular plan, approximately 60m by 72m in plan and 18m in height. Two smaller mid-floors 12m by 72m also appear at one side of the structure, halving the 9m height of the larger, main ones. The structural system is moment-resisting (portal) frames along the transverse 72m dimension and concentric x-braced frames along the longitudinal 60m dimension. It has been designed according to the Iranian Code of Practice (Standard No. 2800) for seismic loads. The building incorporates some mass irregularities due to the presence of mid-floors, thus exhibiting some eccentricity and consequently torsional characteristics. The roof diaphragm is also relatively flexible, essentially featuring a 72m long span that is only supported at the sides. In addition, the building incorporates long 14-16m beams supporting the first-floor composite slab, with potentially compromised composite action due to poor construction detailing and quality, which are vulnerable to vertical vibrations.

Notably, to resolve the floor vibration problem, a strengthening scheme—which involved diagonal braces, connecting the girder to the column and adding extra columns—was adopted in a very similar, to the one considered here, part of the industrial building. It was found to only marginally improve the overall floor vibration performance (see Fig. 1). The following paragraphs will investigate the abovementioned issue to (a) explain the reasons behind the failure of the previously applied rehabilitation scheme and (b) propose an efficient alternative.

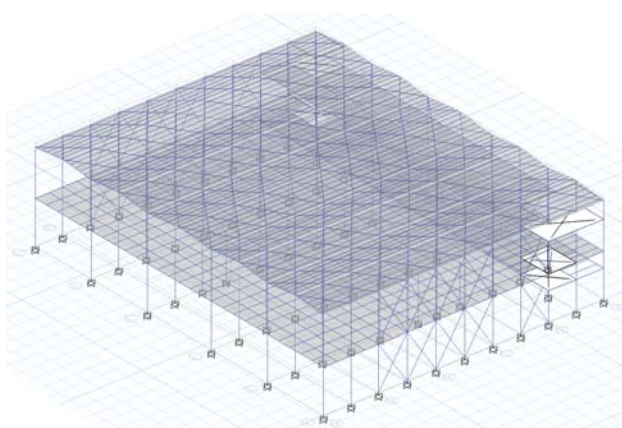


Fig. 1 The structural model of an ineffectively strengthened building part (similar to the one analysed here but slightly bigger in plan) as provided by the client.

4. FLOOR VIBRATIONS

4.1 Outline of the analytical methodology

To assess the vibration performance of the floors and consequently propose an adequate strengthening scheme, linear dynamic analyses were carried out using the OpenSees analysis platform [1]. The testbed for our floor vibration analyses was a 14m long girder.

The girder was modelled using an elastic beam-column element with two rotational springs at its ends. The stiffness of the composite beam was effectively calibrated (i.e. a reduction factor was applied) to account for the suspected deficiencies in the composite floor action, due to improper construction quality. The model also accounted for the flexibility induced to the main girder by the supported joists, essentially considering the fact that we are dealing with a two-way composite slab system. This was achieved by suspending the nodal masses at the girder-to-joist intersection points with translation springs whose stiffness was also adequately calibrated. The overall goal of the model calibration process was for the slab to vibrate at approximately 4.5Hz when the girder is unstiffened and at 5.5Hz when it is stiffened with the use of the diagonal braces. The latter frequency essentially represents the marginal improvement in the slab vibration performance, measured via field vibration testing, following the application of the unsatisfactory rehabilitation scheme in an almost identical building wing.

A small 10kN (1tn mass) forklift is adopted as the standard loading condition. The vertical load timehistory is modelled as a symmetric triangular pulse of 1sec total duration. As all elements are essentially operating in the linear range, larger vehicles will cause proportionally larger effects. The performance of the first-floor slab is tracked via the midspan displacement (typically negligible) and the midspan acceleration. Fig. 2a and 2b illustrates the current condition of the building. Significant accelerations are to be expected that will persist over several seconds. The results will be even worse for heavier vehicles or trains of vehicles, which are known to operate in the building. The rehabilitation scheme adopted for a similar building wing, as can be seem in Figs 2c-d, can only marginally improve the situation, as several bending modes of the slab elements are not sufficiently stiffened. Apparently, in both cases the vibrations take several seconds to be damped.

4.2 Proposed rehabilitation scheme

The utilization of energy dissipation systems for enhancing the vibration as well as the seismic performance of new or existing structural systems (e.g. buildings, bridges etc.) steadily increased in the past few decades. The damping systems can vary quite a lot from devices that undergo inelastic deformations (e.g. yielding devices) to others having a viscous/viscoelastic (e.g. fluid viscous devices) behaviour [2]. When it comes to stiff structures, like the one showcased here, which in general undergo small drifts under earthquake or wind loading, or in the case of serviceability vibration conditions, such as the floor vibrations induced by human activities or machine operation, which again are paired with small drifts and small velocities, care should be exercised in selecting and designing the structural control systems. In fact, the small displacements associated with the aforementioned structural typologies or loading conditions could well render the viscous damping devices, which are deemed to be among the most efficient energy dissipation systems, ineffective, due to their activation displacement and velocity being lower than the induced displacement demands [3]. To resolve this issue, Constantinou *et al* [2], proposed the use of a displacement amplification scheme, namely Toggle Brace Damper (TBD) system. The latter, depending on its geometry, it was found to amplify 2-5 times the damper strokes compared to the deformation experienced by the structural system.

This study employs a similar TDB system. The geometry of the selected configuration, which is illustrated in Fig. 3a, was determined based on its efficiency but also having in mind the operational restrictions associated with the building use as an industrial plant.

From Fig. 3a it can be inferred that the viscous damper in the selected scheme is directly connected in the beam-to-column joint using a pinned support. A similar pinned support is applied to its other end as well, which intersects with two diagonal braces being used to transfer the resulted forces to the beams and columns of the structural frame. Different configurations may be considered to provide additional support to the beam for improved vibration control. Further lowering of the connection to the column from a 4.5m height from the ground to 2.5-3m significantly improves vibration characteristics, but this choice needs to be considered subject to operational and access limitations.

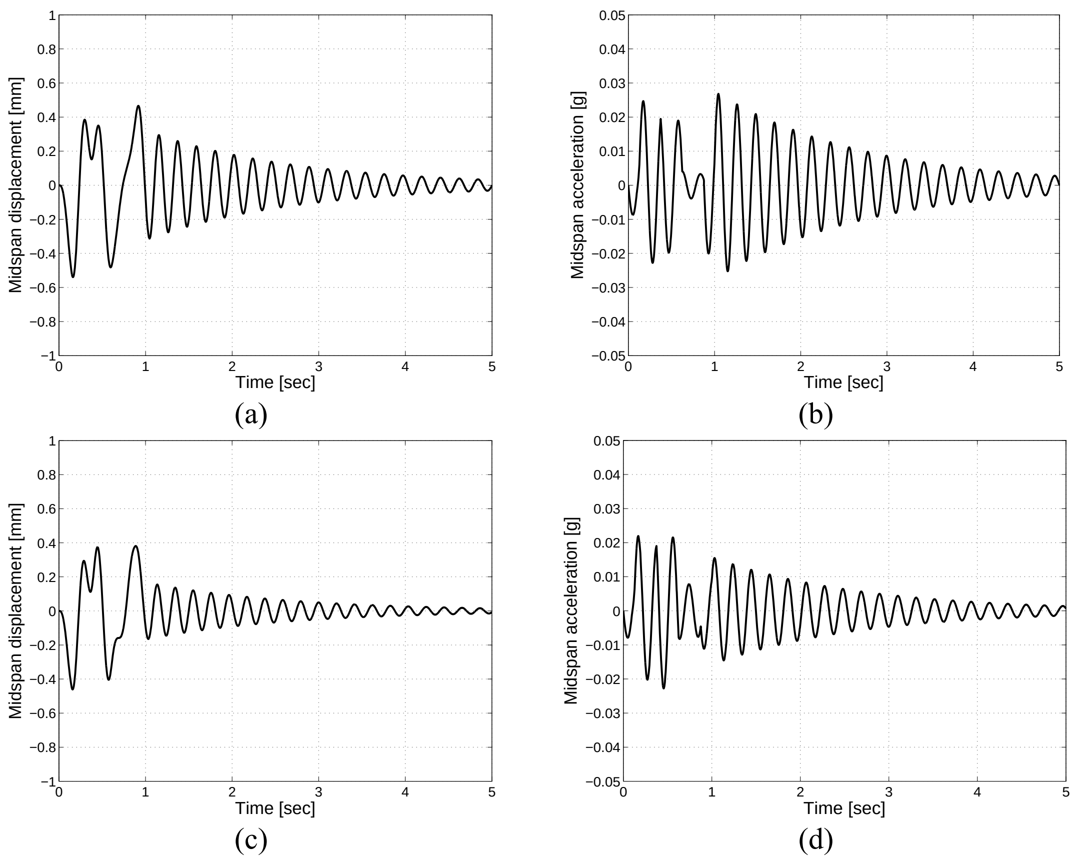
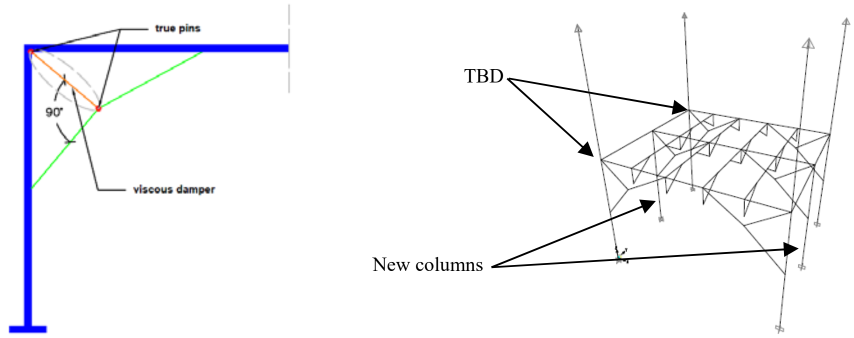


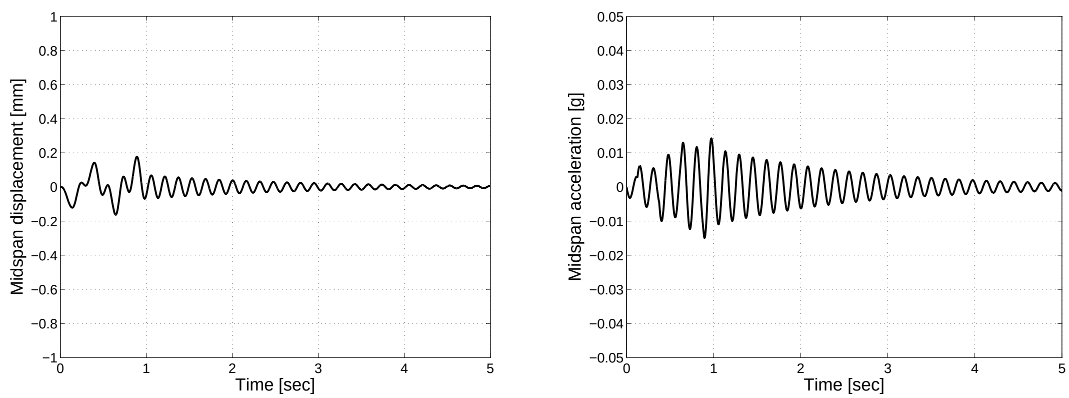
Fig. 2 (a) Maximum midspan displacement 0.54mm and (b) maximum midspan acceleration 27mg for the as-constructed 14m long main girder supported only at the ends and (c) Maximum midspan displacement 0.46mm and (d) maximum midspan acceleration 23mg for the rehabilitation scheme with the main girder supported at the ends and by two struts added at a quarter of its length from the ends.

Further to the TBD system installation, the joists spanning on the main girders needs to be also strengthened. A strengthening scheme that involves diagonal structs at 1/3 and 2/3 of their length was adopted (see Fig. 3b). This was considered to be a necessary rehabilitation measure in order to further increase the floor's fundamental frequency as well as control the vertical mode shapes associated with the joists. The introduction of the joist stiffening struts and the toggle braces was proven to resolve the vibrations, as long as the toggle braces can be attached at least at the mid-height of the columns ("limited rehabilitation scheme", see Fig. 3a-b), or ideally even lower closer to the column base ("proposed rehabilitation scheme" in which the braces connected to the columns are located 3m from the column bases). It is worth noting that in order to create a regular column grid to accommodate the TBD, 16 new columns have been added at all main girder ends. For a typical part of the slab, the position where these the new columns have been added is also illustrated in Fig. 3b.

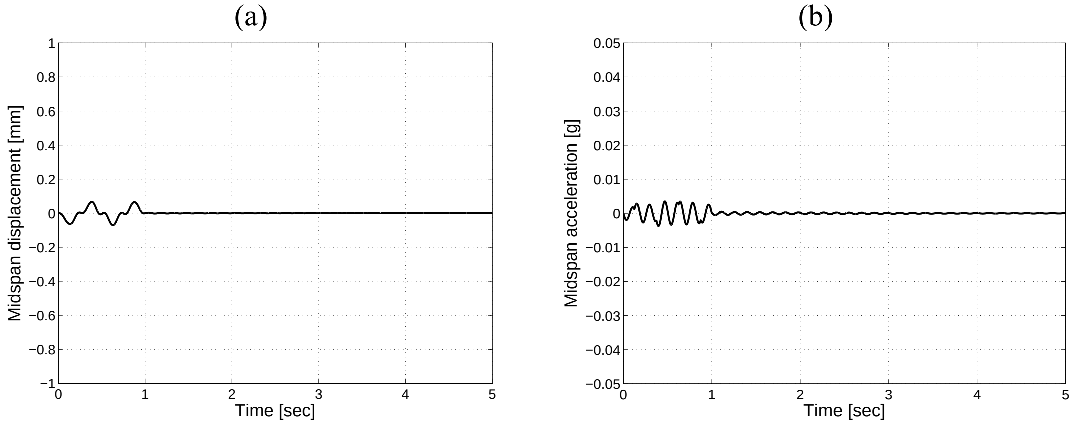


(a) (b)

Fig. 3 (a) Single toggle brace detail. Two are placed in each portal frame bay of the first floor and (b) "as modelled" 14x12m part of the slab showing the TBD and the joist strengthening scheme for the "limited rehabilitation scheme" (TBD attached at mid-height of column).



(a) (b)



(c) (d)

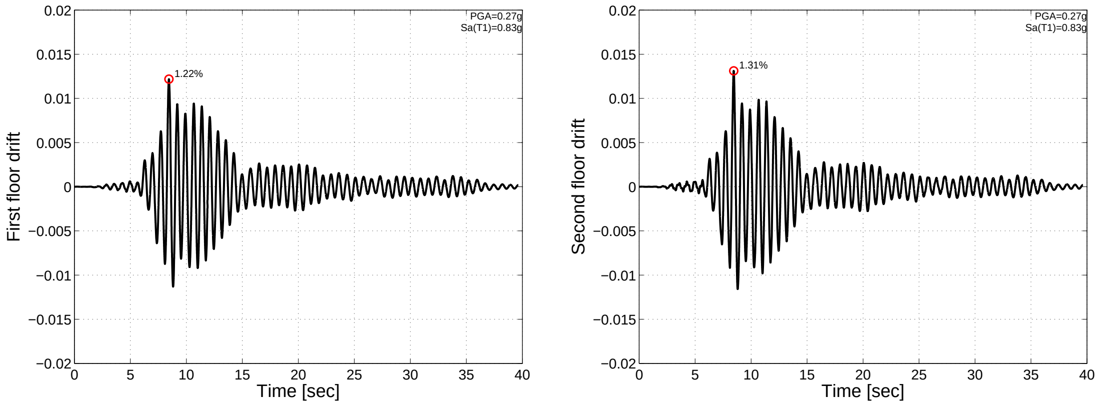
Fig. 4 (a) Maximum midspan displacement 0.18mm and (b) maximum midspan acceleration 15mg for "limited rehabilitation scheme" and (c) Maximum midspan displacement 0.07mm and (d) maximum midspan acceleration 3.7mg for the "proposed rehabilitation scheme".

For the “limited rehabilitation scheme” the fundamental frequency of the floor slab was found to be approximately 9.8Hz, whereas in the case of the “proposed rehabilitation scheme” this was further increased to 11.3Hz. According to the AISC Design Guide for Floor Vibrations [4] with reference to human activity though, vibrating floors usually have frequencies ranging from 5 to 8Hz. By comparing Figs 2 and 4 it is evident that the improvement in the vibration performance of the composite floor is significant. In particular, for the “limited rehabilitation scheme” the maximum mispan acceleration is about half the acceleration of the current state and the vibrations beyond 2sec are expected to be minor. Even better, for the “proposed rehabilitation scheme” the maximum midspan acceleration was found to be less than 15% than that of the current state and the slab experiences no discernible vibrations beyond 1sec. In general, the dampers do not dissipate appreciable energy for the 10kN vertical load due to the small magnitude of the velocities and displacements considered, mainly operating as regular truss elements in the normal range of operation. Still, they can offer some dissipation and reduce the duration of oscillations of the slab if larger vehicles are used. Thus, it is sufficient to use small dampers in every other girder (i.e. every 12m), mainly to mitigate horizontal deformations and only secondarily for vertical ones. However, in all girders we will install toggle braces, either with or without dampers (see Fig. 3b) to provide sufficient stiffening against the vertical oscillations.

5. PRELIMINARY ASSESSMENT FOR SEISMIC LOADING

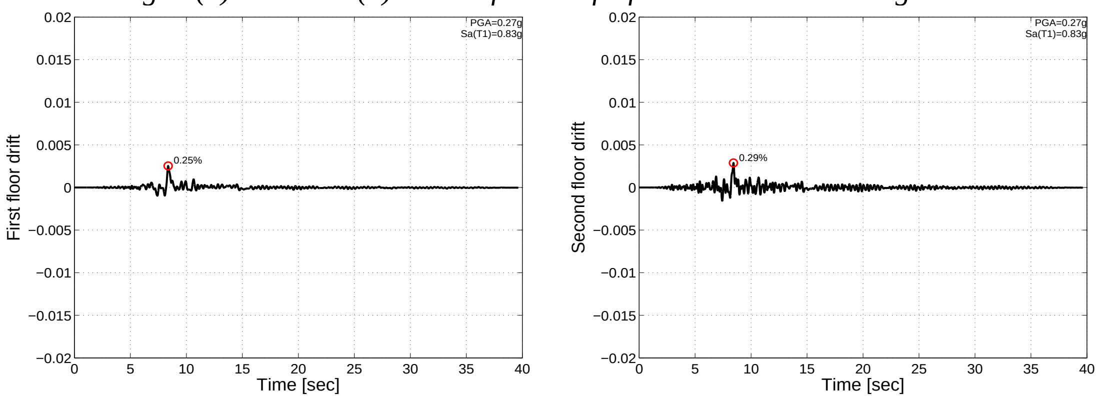
Further to the addition of the columns and the TBD in the first floor, a total of 12 dampers are proposed to be placed in single diagonal bracings in the second floor. Six will be used in the longitudinal direction and six in the transverse. All damper bracings shall utilize no-slip connections. The longitudinal braces will be placed close to the midspan of the 72m building width to better support the flexible roof diaphragm, while transverse braces (along portal frames) will be placed closer to the sides to allow for better torsion control. Furthermore, it was suggested for all X-braces in both floor levels to be strengthened.

As expected, the dampers bring considerable benefits to the system response. Depending on the size of the dampers used and the number of dampers chosen, one can obtain from good to overwhelmingly good response qualities. An example of the effect of using 62 small dampers is illustrated in Figs. 5 and 6 for a single earthquake event having a peak ground acceleration of 0.27g. A comparison of Fig. 5 for the original building with Fig. 6 for the rehabilitated one shows a good degree of improvement, whereby building drifts are reduced by more than 80%. Different events will show different levels of improvement, but overall the trend is expected to be similar, never falling above 60-70% of the original values.



(a) (b)

Fig. 5 (a) First and (b) second floor drifts for the current building state.



(a) (b)

Fig. 6 (a) First and (b) second floor drifts for the rehabilitated building.

6. CONCLUSIONS

A strengthening scheme has been proposed for an industrial case-study building to resolve floor slab vibration issues as well as earthquake loading related concerns. It was proven that the use of toggle-brace dampers along with classical strengthening measures (i.e. extra columns to acts as props, diagonal braces in joists, strengthening of X-braces) could result in major improvements with reference to the overall building performance. The use of toggle braces to amplify the small vertical drifts associated with the floor vibrations, as well as the horizontal ones related to the response of the stiff industrial building to seismic excitations, is believed to be key towards maximizing the effectiveness of the viscous dampers in both the considered loading conditions. The proposed measures are expected to bring the behaviour of the building well within the requirements of international standards, eliminating vibration issues and essentially reducing its probability of experiencing any level of seismic damage and loss throughout its lifetime by more than 50%.

7. REFERENCES

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ΕΛΕΓΧΟΣ ΤΑΛΑΝΤΩΣΕΩΝ ΣΥΜΜΙΚΤΟΥ ΒΙΟΜΗΧΑΝΙΚΟΥ ΔΑΠΕΔΟΥ ΥΠΟ ΦΟΡΤΙΑ ΚΡΟΥΣΗΣ ΚΑΙ ΒΕΛΤΙΩΣΗ ΤΗΣ ΣΥΝΟΛΙΚΗΣ ΣΕΙΣΜΙΚΗΣ ΕΠΙΛΕΣΤΙΚΟΤΗΤΑΣ ΜΕ ΤΗ ΧΡΗΣΗ ΑΠΟΣΒΕΣΤΗΡΩΝ ΣΕ ΔΙΑΓΩΝΙΑ ΔΙΑΤΑΞΗ ΜΕ ΕΓΚΑΡΣΙΑ ΑΝΤΗΡΙΔΑ

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ΠΕΡΙΛΗΨΗ

Η εν λόγω εργασία αφορά στην παρουσίαση μίας περιπτωσιολογικής μελέτης που πραγματοποιήθηκε για τη βελτίωση αφενός της δυναμικής συμπεριφοράς μίας διέρειστης σύμμικτης πλάκας υποκείμενης σε κρουστικά φορτία, και αφετέρου της συνολικής σεισμικής επιτελεστικότητας του υπό εξέταση βιομηχανικού κτιρίου. Για την επίτευξη του προαναφερθέντος διττού στόχου χρησιμοποιήθηκαν αντηρίδες καθώς και ιξώδεις αποσβεστήρες σε διαγώνια διάταξη με εγκάρσια αντηρίδα. Αναφορικά με τον έλεγχο των ταλαντώσεων του δαπέδου, το προτεινόμενο σχέδιο ενίσχυσης και στις δύο διευθύνσεις του κτιρίου είχε ως στόχο η φυσική ιδιοσυχνότητα του συστήματος πλάκας-διαδοκίδας-κύριας δοκού να είναι πολύ μεγαλύτερη από τα προτεινόμενα ελάχιστα όρια. Η επιλογή τοποθέτησης των αποσβεστήρων σε διαγώνια διάταξη με εγκάρσια αντηρίδα κρίθηκε απαραίτητη προκειμένου (α) να υλοποιηθούν ρηχά δικτυώματα για λόγους λειτουργίας του εργοστασίου, (β) να μεγεθυνθούν οι εγκάρσιες μετακινήσεις της πλάκας λόγω της επενέργειας του κρουστικού φορτίου και (γ) να μεγεθυνθούν οι οριζόντιες σεισμικές μετακινήσεις του υπό ανάλυση δύσκαμπτου βιομηχανικού κτιρίου, ώστε και στις δύο οριακές καταστάσεις (λειτουργικότητας και αστοχίας) να αυξηθεί η ταχύτητα παραμόρφωσης των αποσβεστήρων και να μεγιστοποιηθεί η αποτελεσματικότητά τους.