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Improving Earthquake Resistant Design and Construction in India

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Abstract

New materials and structural systems are being introduced in construction profession every day either to replace conventional materials whose availability is becoming scarce or to improve the efficiency of construction. New systems are also being introduced to cater to new demands in functionality and aesthetics. While Indian researchers have kept pace with the theoretical aspects of earthquake resistant design, the practical aspects are hardly touched upon since they require testing and implementation in practice. The current codes are prescriptive about the general requirements for strength and detailing and so are inadequate to define and assess the performance objectives of specific structural systems. Consequently, the gap between academics and profession has been widening and has reached extreme proportions and there is an urgent need to revive applied research in earthquake engineering to evaluate seismic performance of practical systems. In this paper, the work carried out by the author and his students at IIT Madras on seismic design and tests carried out on masonry, reinforced concrete, structural steel, steel-concrete composite, cold-formed steel, semi-rigid frames of steel and composite construction and industrial rack systems are reviewed. The importance of understanding the details of the seismic behaviour of these system towards improving the performance is emphasized.

Keywords: Seismic Design, Masonry, Reinforced Concrete, Structural Steel, Steel-concrete Composite, Cold-formed Steel, Semi-rigid Frames

1. Introduction

During the last few decades, the knowledge on earthquake resistance of various structural systems has increased dramatically across the world. In India, the structural systems have become quite complex due to the introduction of new materials and systems and designs following foreign technology and codes. However, the use of the knowledge and capabilities of the general designers has not kept pace with the developments in the field of earthquake resistant design.

While Indian researchers have kept pace with the theoretical aspects of earthquake resistant design, the practical aspects are hardly touched upon since they require testing and implementation in practice. Meanwhile, new materials and structural systems are being introduced in construction profession every day either to replace conventional materials whose availability is becoming scarce or to improve the efficiency of construction. New systems are also being introduced to cater to new demands in functionality and aesthetics. For every conventional construction, a number of newer forms of construction are carried out with utter ignorance and disregard to their seismic performance. Consequently, the gap between academics and profession has been widening and has reached extreme proportions and there is an urgent need to revive applied research in earthquake engineering to evaluate seismic performance of practical systems.

A similar story exists between the development of technical resources and guidelines for earthquake resistant construction practice. Although, foreign sources are sometimes available, their use is often inconvenient and applicability in Indian conditions is questionable. To complicate matters further, the teaching and continuing education programs have not kept pace with the industry requirements. The current codes are prescriptive about the general requirements for strength and detailing and so are inadequate to define and assess the performance objectives of specific structural systems.

There is an urgent need to narrow the gap and achieve adequate protection and resilience against earthquake disasters. This was underscored by several seismic events among which the Gujarat earthquake of 2001 was prominent. Some steps were taken to bridge the gap by several agencies and government bodies but these have been too meagre and have lost their momentum over a period of

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time. In this paper, some of the structural systems on which research and development is required to achieve seismic safety are identified.

2. Seismic Performance of Structural Systems

A variety of structural sections, members and systems are used in practice to cater to the functional and safety requirements. While RC frames with/without shear walls and Steel Moment and Braced frames are the most common structural systems for which considerable design guidelines are available, a host of other sections, members and connections as well as entire systems which are used in practice do not have adequate guidelines for design. Although, results obtained from cyclic/seismic performance studies of such systems are available in technical journals, there is a need to compile the information into a readily usable form. There are also several topics on which available information is too meager and often incomplete to rely on. Specific studies on such topics need to be researched and tested to develop design guidelines and limitations. Some of these are listed below:

2.1. Alternate Masonry Systems: Although brick masonry remains the most common masonry system, it is fast getting replaced by other types of masonry blocks such as hollow, aerocon and interlocking block masonry. The alternate masonry blocks have advantages such as light weight, better sound and thermal insulation, ease of handling and speed of construction apart from economy. During the Gujarat earthquake, hollow concrete block masonry was found to split into individual withes probably due to the tension developed in the transverse direction due to Poisson's effect. Interlocking blocks (Fig. 1) try to overcome this problem by the effective interlocks between blocks on either side and also presenting hollow cores [1]. It is necessary to study the behaviour of such alternate masonry, with and without reinforcement bands, which can provide better safety since the common brick wall is one of the most dangerous systems during earthquakes, especially when used as an infill in multi-storeyed RC frames. The reduced weight and stiffness of alternate masonry systems may also improve the seismic performance of such frames. The building industry is also using precast panels to improve the speed of construction.

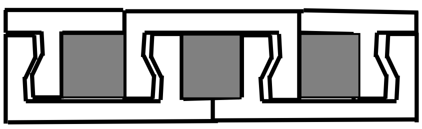


Fig. 1 Hollow Interlocking Block Wall

2.2. Reinforced and Pre-cast Concrete Construction: With reference to Reinforced Concrete (RC) Structures, adequate guidelines are available for designing and detailing of Cast-in situ frames of normal strength concrete. In recent years, higher strength concrete has become more economically viable but its use in earthquake resistant design is limited due to the relatively low ultimate compressive strain limits. Efforts to improve the crushing strain by adding variety of steel/polypropylene fibers need to be undertaken to enable more efficient design and construction. Strengthening and Confinement by FRP sheets can also be tried along with studies on the durability of such procedures. Alternative reinforcement details can also be used to improve the seismic performance of RC beams and joints [2]. The performance-based design of RC frames was studied by Venkateswarlu and Satish Kumar [3]. The study was later extended to Open ground storey buildings by Satish Kumar and Srinivasan [4].

Pre-cast construction has taken off in a big way in India during recent years and guidelines for their design are urgently needed to ensure their seismic performance. Use of shear walls in conjunction with pre-cast gravity load resisting systems is also being undertaken but guidelines to ensure the deformability of precast systems without impairing their gravity load resistance are not readily available. The construction joints in cast in-situ shear walls are known to give poor seismic performance. Nowadays, precast panels are being used to construct shear walls with cast in-situ joint details. Such details need to be improved to ensure better seismic performance.

Repair and retrofitting of damaged or deficient RC structures is an important area which enables salvaging the unsafe building stock at economical costs. While the techniques for gravity loads are well known, the same cannot be used reliably for seismic loads. Hence it is necessary to verify the efficacy of various techniques with respect to their ease, cost and efficiency and the resulting enhancement in seismic performance [5].

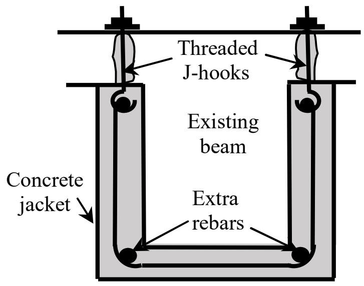


Fig. 2 Beam retrofit

2.3. Structural Steel Multi-storeyed Buildings: General guidelines for seismic design of Steel moment frames and concentric braced frames are available. However, guidelines for seismic design of conventional beam-to-column connections such as top-seat angle web cleat connection and extended/flush end-plate connections need to be developed for rolled and built-up beam sections. High strength steel up to 700 MPa with adequate elongation and notch-toughness is also readily available but is not recommended for seismic resistant frames due to the brittle performance and welding issues expected. Efforts to enable their use by adding ductile links into the system can be undertaken. Innovative connections can be used to solve seemingly difficult connection problems. Fig. 1 shows one such connection between a box beam and a box column effected through an opening in the web [6]. The connection was found to be semi-rigid with its rigidity depending on the depth of the channel connectors welded to the column. A parametric study was carried out to characterize the behavior of the connection.

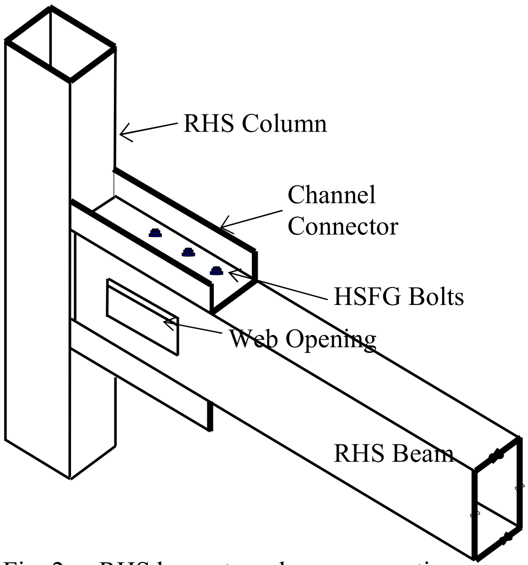


Fig. 2 RHS beam-to-column connection

The cost is reduced since it uses conventional bolts available in the market rather than custom made threaded rods. Also, the bolt holes in the beam flange make it act like a reduced beam section (RBS) developed after the Northridge Earthquake of 1994 so as to avoid the brittle failure in the welds.

2.4. Structural Steel Industrial Buildings, PEBs, Conveyors/Pipe Racks, Power Plant Structures: Steel Industrial Buildings are used as single storied buildings for production facilities and warehouses have light roofs and so are often governed by wind, they are also characterized by low structural indeterminacies and slender web sections, both seriously limiting their ductility [7]. Also, bracing members are often too long making it difficult to satisfy overall slenderness limits specified for braced frames. Thus, it is important to understand the seismic performance of such structures and develop guidelines for their design.

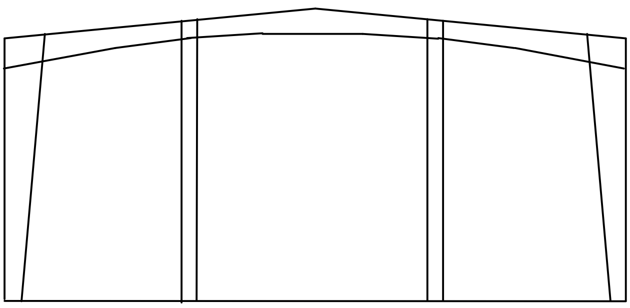


Fig. 3 Industrial Building Frame

Several Industrial buildings used as material handling systems such as conveyors and pipe racks, material storage and processing buildings such as boiler buildings, silos, bunkers and crushers, waste handling systems such as Mechanical Dust Collectors and Electro-static precipitators. are characterized by heavy loads and/or large heights and the usual seismic design procedures become quite expensive. At the same time, these are critical structures that need to function after a severe earthquake. Hence innovative energy dissipaters need to be devised to protect these structures from earthquake loading.

2.5. Steel-concrete Composite Construction: Steel-concrete Composite Construction has several advantages over pure steel or reinforced concrete construction. Apart from more efficient use of the two materials and enabling faster construction, these structures give the double benefit of reducing the mass as well as stiffness leading to superior seismic performance. The Profiled deck slabs and composite beams can reduce the floor mass considerably by removing most of the concrete below the neutral axis. The column free area of profiled deck and RC slabs are often increased by using light steel beams made of cold-formed sections. However, the diaphragm behaviour of such slabs is questionable and it may be safer to assume them as flexible diaphragms.

The connection between composite beams and columns may be subjected to significant reversal of moments. Hence it is necessary to clarify the cyclic behaviour such connections [8] and frames [9].

Steel-concrete composite columns are either concrete-filled tubes (CFTs) or concrete-encased sections (CESs). While the former have higher strength and ductility, the latter offer better fire resistance. Although, the concrete-filled tubes have been well researched, their main drawback is the difficulties they pose for connecting beams. Concrete-filled RHS were tested under high axial loads and cyclic bending by Velmurugan and Kumar [10] and found to have high ductility and energy dissipation capacities.

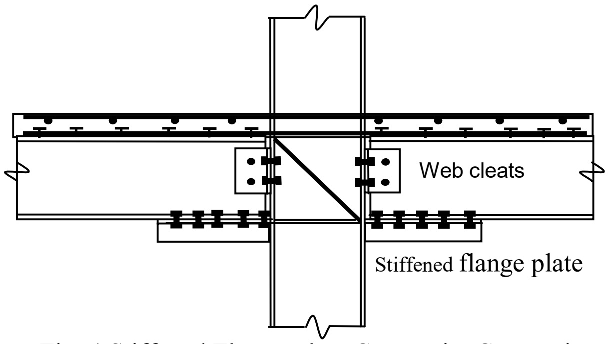


Fig. 4 Stiffened Flange-plate Composite Connection

Concrete-encased sections on the other hand may have somewhat lower ductility but are far easier to connect. In fact, the beams may be first connected to the steel column and later the column encased in concrete. There is an urgent need to develop guidelines for their earthquake resistant design [11].

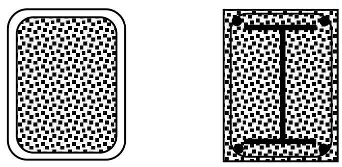


Fig. 5 Concrete-filled Tube and Concrete Encased Section

2.6. Cold-formed (CFS) Steel Buildings, Tubular Frames: Cold-formed steel (CFS) structures, also known as Light Gauge Steel (LGS) Structures, despite their several advantages are yet to take off in India in a big way. Their advantages include higher strength to weight ratio compared to even hot-rolled steel sections, ease of handling and speed of erection, better durability due to the superior paint systems used and sustainability due to the possibility of reuse and recycle. They are ideally suited to earthquake resistant construction due to their lighter weight and flexibility. Since their ductility is limited due to local, global (flexural and flexural-torsional) and distortional buckling modes, they need to designed to ensure adequate seismic performance.

Previous studies have relied on the strength and stiffness of infill panels made of gypsum or calcium silicate boards. However, it has been found that developing moment connections between members leads to better seismic performance. Also use of Self-drilling Screws (SDS) in place of bolts gives better performance [12, 13].

In particular, frames using RHS can avoid other buckling modes but undergo local buckling under severe cyclic loading. Their ductility will depend on the width-to-thickness ratios and axial load ratios. cold formed rectangular hollow sections were tested by Srinivas [14] under higher axial load ratios (ratio of actual axial load to squash load). The sections were of size 172 mm x 92 mm x 5.4 mm (b/t = 30) and cold-formed with rounded corners. Axial load ratios for the two specimens were 0.8 and 0.6. Cyclic lateral loads were then applied in incremental amplitudes. The specimens had cyclic ductilities of 5.5 and 8.5, respectively. It was concluded that these were adequate for their use in special moment frames.

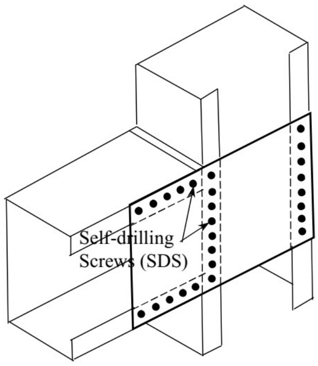
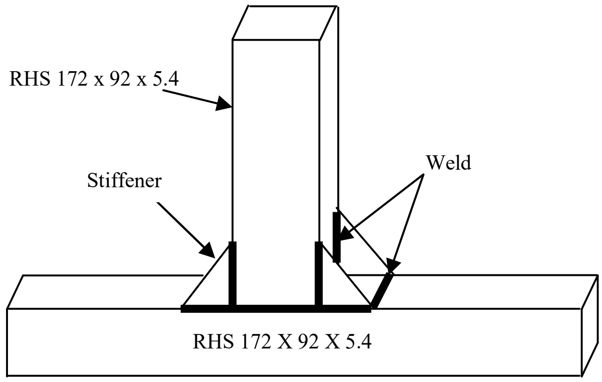


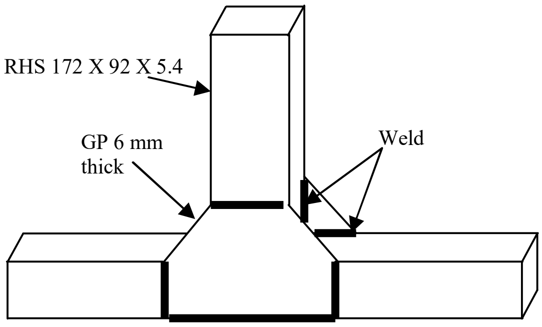
Fig. 6 Moment Connection between Cold-formed Sections.

In an another study by Durlabh and Satish Kumar [15], two moment connection between rectangular hollow sections were tested under cyclic loading and found to be stronger than the connected sections so that local buckling occurred away from the connection. A photo of one of the connections is shown in Fig. 3 where the full plastic moment of the section was achieved and failure occurred outside the connection.

A two-storeyed pinned-base frame with beams of rectangular hollow sections was tested by Satish Kumar and Arun Sekar [16] to study the effect of strength and stiffness degradation of hinging regions on the seismic performance of frames.



(a) Slit Box Stiffener Connection



(b) Gusset Plate Stiffener Connection

Fig. 7 RHS Moment Connections

2.7. CFS-SCC Combinations, modular construction: Cold-formed sections and trusses are finding increasing applications as secondary beams in high-rise structures. Making cold-formed steel sections and trusses act composite with concrete slabs will not only make the systems structurally more efficient but also lead to a reduction in weight thereby improving the seismic performance [17].

Modular construction where the building is shop manufactured in modules and simply stacked in the field is also being carried out in India. The seismic performance of such structures needs to be studied and efforts to improve the performance should be undertaken.

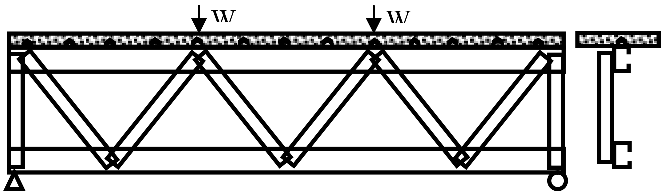


Fig. 8 Cold-formed steel-concrete composite truss

2.8. Special Frames for Improved Performance: Semi-Rigid Frames (SRF) with partially-restrained connections are known to be economical over conventional topologies and IS800:2007 has brought the subject back into focus. Adequate information is available on the moment-rotation curves for various connection types and the design of semi-rigid frames. Even the concern on excessive lateral drift during seismic loading has been addressed. It has been found that there is a considerable reduction in seismic load due to the increased flexibility when compared to rigid moment frames. Also past earthquakes have shown that rigid connections tend to develop brittle fracture and some flexibility in connections is desirable to achieve better performance. However, semi-rigid frames have not been used extensively in seismically active regions due to unavailability of guidelines for their seismic design. On the other hand, in relatively less seismic regions, semi-rigid frames would be more economically viable alternatives to rigid frames. Satish Kumar and Pavan Kumar [18] studied the non-linear seismic performance of semi-rigid steel frames and compared it with the response of rigid frames. They carried out a parametric study by varying connection stiffness and strength and evaluate the seismic ductility demands on semi-rigid steel frames and connections. The design guidelines developed can be used to achieve significant economy in connection design without compromising on the drift limitation.

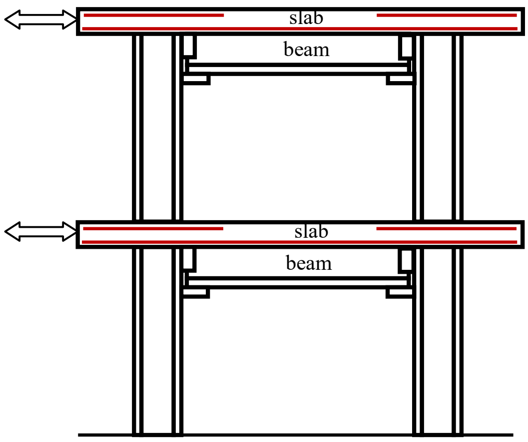


Fig. 9 Composite Frame with Semi-rigid Connections

Senthilkumar and Satish Kumar [9] have proposed design guidelines for semi-rigid steel-concrete composite frames so as to satisfy strength, deflection and seismic drift limits. They compared the seismic performance of a rigid and semi-rigid frame, designed to satisfy current codal provisions, by carrying out non-linear static pushover analysis. The comparison indicates that, in low to moderate seismic areas, frames with semi-rigid connections can be designed to perform satisfactorily, thereby reducing the connection costs and the overall cost of the structure.

The Special Truss Moment Frame (STMF) is used for relatively long bay widths. The purpose of STMFs is the design of a special segment inside the truss to yield in a ductile manner while the other members outside the special segment stay in the elastic range (AISC 1997).

The Vee and inverted-Vee braced frames, although classified as concentrically braced frames, have the advantage that the bracing takes a part of gravity loads by dividing the beam span into two. Also the frames can easily accommodate openings for doors and windows. These frames can be advantageous in the low-seismic regions where large investments in lateral load resisting systems may be unwarranted.

In eccentrically braced frames (EBF), the brace is connected to the beam at a slight distance away from the beam to column connection making it eccentric. The part of the beam between the brace connection and the column connection is known as the link. Under seismic loading, the link beam dissipates energy primarily by inelastic shear deformation of its web. This also ensures that the force transferred to the brace and column is limited thereby avoiding the brace buckling. The preclusion of brace buckling in EBFs permits stable hysteretic behavior under the most severe cyclic loading conditions. More details on the design of these frames can be found in AISC 2016 [19].

2.9. Frames with Energy Dissipating Systems: Global buckling has always been a problem to contend with in steel design. Especially with bracing members, limiting slenderness always governs the design. Braces perform extremely well in tension but when the load reverses, as is the case during seismic loading, the braces suffer irreversible buckling under compression. This leads to a reduction in energy dissipation capacity. To overcome this problem, the brace can be put inside an outer tube or sleeve and the gap between the two filled with grout (Fig. 8).

Fig. 10 Concept of a Buckling Restrained Brace

This will prevent the brace from buckling in its fundamental mode and the brace is forced to buckle in a much higher mode thereby significantly increasing its strength and stiffness. Tests conducted by Vijith [20] have shown that the hysteretic loops are well rounded leading to considerable increase in its energy dissipation capacity (Fig.9). Another useful feature is that by using a non-prismatic cross section, the strength and stiffness can be independently varied to some extent and this helps in choosing the optimum bracing for improved performance of multi-storeyed frames [21].

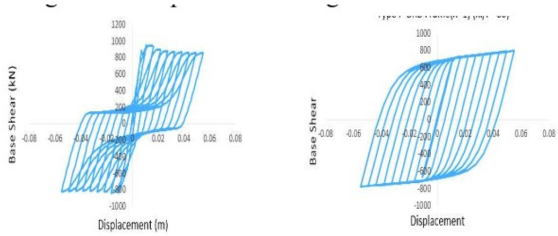


Fig. 11 Hysteretic Behaviour of conventional and Buckling-restrained brace (KL/r = 80)

A single bay ten-storey concentric braced frame with diagonal Non-Buckling bracing was studied by Ravikumar et al [22] for its performance under seismic loading. Non-linear time history analysis was carried out using SAP2000 to study the variation of maximum base shear, roof displacement, inter-storey drift, damage index and stresses in various members due to El-Centro earthquake accelerogram. It was observed that Non-Buckling bracings are effective in dissipating energy and controlling inter-storey drift. The use of Bucking-restrained braces in bridges has been investigated by Dutta and Kumar, [23].

The stable post-buckling behaviour of steel plates in shear has long been recognized in relation to the failure of plate girder webs. The extra reserve strength available due to tension field action was quantified for use in design under static load conditions. It was only a matter of time until the same was extended to cyclic loading. Consequently, The steel plate shear wall (SPSW) system has emerged as an efficient alternative to other lateral load resisting systems such as reinforced concrete shear walls. Guidelines for the use of SPSWs are given in ANSI/AISC 341(2016).

2.10. Industrial Racks: Industrial racks made of cold-formed steel sections are increasing exponentially in India. Pallet racks used to store industrial products are made of cold-formed steel beams and uprights designed for easy installation and changeable configuration. The load carried by the structure as compared to its own weight is very high. Typical connections between beams and uprights are effected through clips engaging in slots and are semi-rigid making the frames very flexible in the down aisle direction. When subjected to seismic loads, the resulting large displacement coupled with high pallet loads can lead to significant second-order effects leading to collapse in the down aisle direction. Also the yielding of connections can lead to a collapse mechanism formation along this direction. Therefore, there is a need to limit the lateral (sway) deflection of racks under earthquake loads. The limiting deflection could also vary with the performance criteria stipulated based on the importance of products stored and the needs of the client. There is an urgent need to study the seismic performance of these systems and develop guidelines for their design [24].

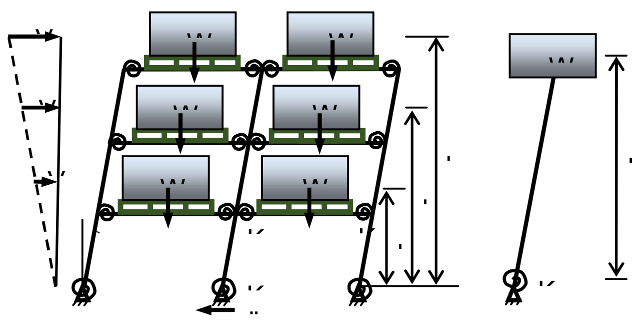


Fig. 12 Pallet Rack System and its SDOF Idealization

3. **Summary and Conclusions:** Even traditional materials such as steel and concrete are now available in newer types and forms. Enormous aluminium-glass curtain walls, pre-cast concrete, pre-engineered metal systems etc are being adopted widely in construction. Currently design codes do not exist on most of these materials and systems for use as structural or non-structural systems and it is left to the design engineer or architect to decide their functionality and safety. This has also led to the practice of using foreign codes, often incorrectly, to design structures. There are no mechanisms in place to ensure that the codal procedures have been followed correctly before construction both in design and in the materials used. The onus is on the designer to ensure the safety and only when failure occurs, the design process is looked into and the materials are tested [25].

Disclosures

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