Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.V)

7-7-10

STRUCTURAL CONSIDERATIONS IN THE DESIGN AND CONSTRUCTION OF A 30 METER HIGH AUTOMATED STORAGE RACK-SUPPORTED FACILITY

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ABSTRACT

This paper summarizes the structural considerations made in the design and construction of a special type of steel structure; the high-rise automated storage and retrieval facility, in which the structural system comprises only light gauge storage rack components. Storage rack frames are fabricated of small, cold formed, light gauge tubes, pipes and channel sections. Seismic design criteria included a requirement to remain essentially elastic during a maximum credible level earthquake ground shaking. Known as "rack-supported buildings", very few such buildings have been constructed in highly seismically-active regions. The case-study outlined herein represents one of the first to be constructed in California.

INTRODUCTION

Computer-controlled random access automated storage and retrieval systems have proved themselves to be extremely efficient and cost-effective in high volume, rapid turnover warehousing of pallet-stored merchandise. As a result, dedicated, single-purpose facilities of this kind have proliferated throughout the United States in the last decade. The efficiency of these facilities may be measured in several ways, one of which is the ratio of the cube capacity of pallet storage to the volume enclosed within confines of the structure. Another measure relates the cube storage capacity to the floor area involved. In this case study in which the overall building height is approximately thirty (30) meters and the gross floor area is approximately 11,000 square meters, these two (2) efficiency measures are evaluated as forty per cent (40%) and twelve (12) cubic meters of storage/square meter of floor area, respectively. The total pallet storage capacity is 57,150. Pallets are all 1.37 m x 1.22 m in size. A fixed configuration of storage provides for unit pallet loads to vary in height in increments of 1.07 m, 1.37 m, 1.83 m and 2.03 m. The warehouse operation involves the use of stacker cranes to store and retrieve pallets. The stacker cranes are designed to traverse the length of aisles located between storage racks, while simultaneous vertical stacker crane cab movement facilitates access to elevated pallet locations. Operational tolerances and capacity, limited the vertical travel motion of the stacker cranes to approximately thirty (30) meters, thereby governing the overall building height. Area-wise, fire insurance considerations dictated sub-dividing the facility into two (2), approximately equal, fire compartments.

STRUCTURAL SYSTEM

Historically, pallet rack storage facilities have been designed to be self-supporting at least for vertical loads, and housed within a structurally-separated building shell. On occasion, high pallet storage rack configurations sometimes have received lateral support from the lateral-force resisting system of the building shell, insofar as they are connected to the building shell roof construction. In this case study, there is no building shell structure whatsoever. The pallet storage racks are designed to be totally self-supporting. The exterior roof and sidewall cladding is simply attached to pallet storage framing. Plates I and II illustrate the nature and modular configuration of the 30 meter high pallet storage rack framing. Aisles are located at 7.52 m o.c. Four (4) post cross-aisle light gauge tubular steel frames are spaced at 1.50 m o.c. between aisles. The outer 2.03 m wide bays of the cross-aisle frames are diagonally strut-braced. Pin-ended strut action within the 1.52 m wide flue between the cross-aisle frames constrains the lateral motion of the two (2) outer bays to be synchronized and accommodates the fire protection sprinkler feeder piping as well as a full height, full length down-aisle diagonally-braced frame of structural steel construction. The cross-aisle frames directly support fifteen (15) pallet load arm and rail assemblies and are horizontally pipe-braced to the centrally-located down-aisle braced frames. Roof construction comprising light gauge steel decking welded to structural steel framing acts as a horizontal diaphragm to provide limited distribution of lateral seismic loads from one (1) pallet storage rack module to another, in the event of uneven pallet load utilization. Founded upon compacted fill and natural soils, a reinforced concrete matt footing, varying in thickness from 0.50 m to 0.90 m, supports the closely-spaced post configuration of the pallet-storage racks.

The lateral seismic force-resisting system in the cross-aisle direction comprises the 2.03 m wide diagonally-braced frames. These 30 m high frames, Plate II, act as vertical trusses cantilevering from the floor slab-on-grade. Pallet seismic loads are transferred directly to these cross-aisle frames through load arm/rail assemblies. Seismic resistance in the down-aisle direction is provided by the diagonally-braced steel frames, located at the center of the flue space. These 30 m high, 60 to 120 m long frames also cantilever vertically from the floor slab-on-grade and are laterally stayed at vertical intervals by the cross-aisle frames. In addition, they are designed to provide lateral support to a 10 m high low bay structure attached to the high bay structure at the east end. Wind loads in the cross-aisle direction are resisted by the single unit cross-aisle frames located at the north and south walls, Plate I. These frames are designed to span vertically 30 m from the floor slab-on-grade to the roof diaphragm. Down-aisle oriented wind loads are resisted by the seismic force resisting system.

SEISMIC DESIGN CRITERIA

Except for the sidewall cladding cross-aisle frames and the exterior non-structural cladding, the structural design was entirely governed by seismic considerations. The unusual and irregular structural configuration, coupled with a close proximity to California's famed San Andreas Fault, mandated that special seismic design-criteria be prepared, which recognized the dynamic characteristics and response of the structure during anticipated adverse seismic conditions. Because of limitations embodied in the static analysis seismic provisions set forth in the applicable Uniform Building Code, 1982 edition, and other industry codes and standards which normally are utilized in the design and fabrication of storage rack structures, the City of Los Angeles Department of Building and Safety required that their Dynamic Analysis Criteria be followed as a minimum. In essence, this criteria prescribes that for braced frame steel structures, the seismic force-resisting system remain entirely elastic during a maximum credible earthquake (MCE). Yielding and buckling capacity limitations must be observed, under the action of simultaneously-applied orthogonal components of surface ground motion in which 100% of one horizontal component is combined with 30% of the other horizontal orthogonal component and vice versa. Further, vertical earthquake ground motions are also to be considered in conjunction with horizontal earthquake ground motion components. In addition, P-delta effects associated with predicted lateral distortions are to be incorporated, as well as a 1.5% overall drift limitation and 7% of critical damping for a maximum credible seismic event. Gravity loading for the MCE design condition included dead loads associated with the storage rack, building enclosure, stacker crane and other equipment and fifty (50%) percent of the rated capacity of the pallet live load storage. This live load percentage was derived from a comprehensive pallet utilization survey conducted on a comparable warehouse facility. This survey also led to appropriate recommendations relating to the weight distribution of pallet-stored merchandise.

One very important business interruption-related consideration not prescribed by the foregoing criteria, pertains to limiting horizontal cross-aisle accelerations in the structure, to those of the earthquake ground motion experienced at the site. This owner-imposed criterion required that time-dependent dynamic seismic analyses be performed using surface ground motion excitation, representative of the various types, durations and intensities of earthquake source events which may affect the site. Source events considered included;

M8.5 San Andreas Event, ~40 km distance, 60 second duration
M7.5 Hollywood/Raymond Hill Event, ~2 km distance, 30 second duration
M7.5 Newport/Inglewood Event, ~20 km distance, 30 second duration

In order to achieve the desired seismic response with regard to mitigating the amplification of cross-aisle horizontal accelerations up through the structure, a limitation of 1.25 to 1.75 seconds was imposed on the fundamental period of lateral vibration (T) in this direction. Further, the use of load rail stopper devices or abrasive, non-skid tape on the top of the load rails was recommended to provide further assurance of preventing sliding of the plywood pallets on the smooth painted finish of the steel load rails.

SEISMIC DYNAMIC CHARACTERISTICS AND RESPONSE

The three (3) dimensional aspects of the computer modelling was performed on a four (4) bay typical module, Plate II. All structural members were included in the finite element computer model, which comprised beam-column and truss elements to represent the physical structure. The computed fundamental period (T) of lateral vibration of the cross-aisle frames is 1.75 seconds, a value at the upper bound of that specified to control lateral accelerations within acceptable limits. The MCE linear elastic dynamic response calculation indicated a 0.30 m maximum cross-aisle roof displacement, an overall building drift of ~1% and a maximum lateral absolute acceleration of ~half (50%) of gravity. The MCE base shear coefficient approximated 30%. Overturning-wise, the maximum MCE uplift at the typical post condition was computed as ~30N at the post baseplate.

Also the computed fundamental period of lateral vibration (T) of the typical down-aisle braced frame system is 0.34 seconds. This resulted in an MCE design base shear coefficient of 0.75, a maximum drift coefficient of

0.17% and a 50 mm roof deflection. Significant uplift forces associated with MCE overturning, resulted in the use of heavy embedment baseplates at each end of the down-aisle frames.

FABRICATION AND INSTALLATION

In order to achieve the desired structural and seismic performance goals and remain within the normal fabrication and cost picture associated with light gauge steel structures of this type, an innovative concept in joint design had to be developed and implemented. This involved the use of a horizontal "collar" plate as a means of connecting the many tube, pipe, angle and channel members. Fillet shop welding of the 100 mm square tube posts and the 5 mm thick collar plates, allow the thin-walled posts to maintain their structural integrity at vital connection points. Further, the collar plate serves to transmit seismic forces around the light gauge posts, thereby facilitating the use of 2 to 4 mm gauge thick walls in the tube posts.

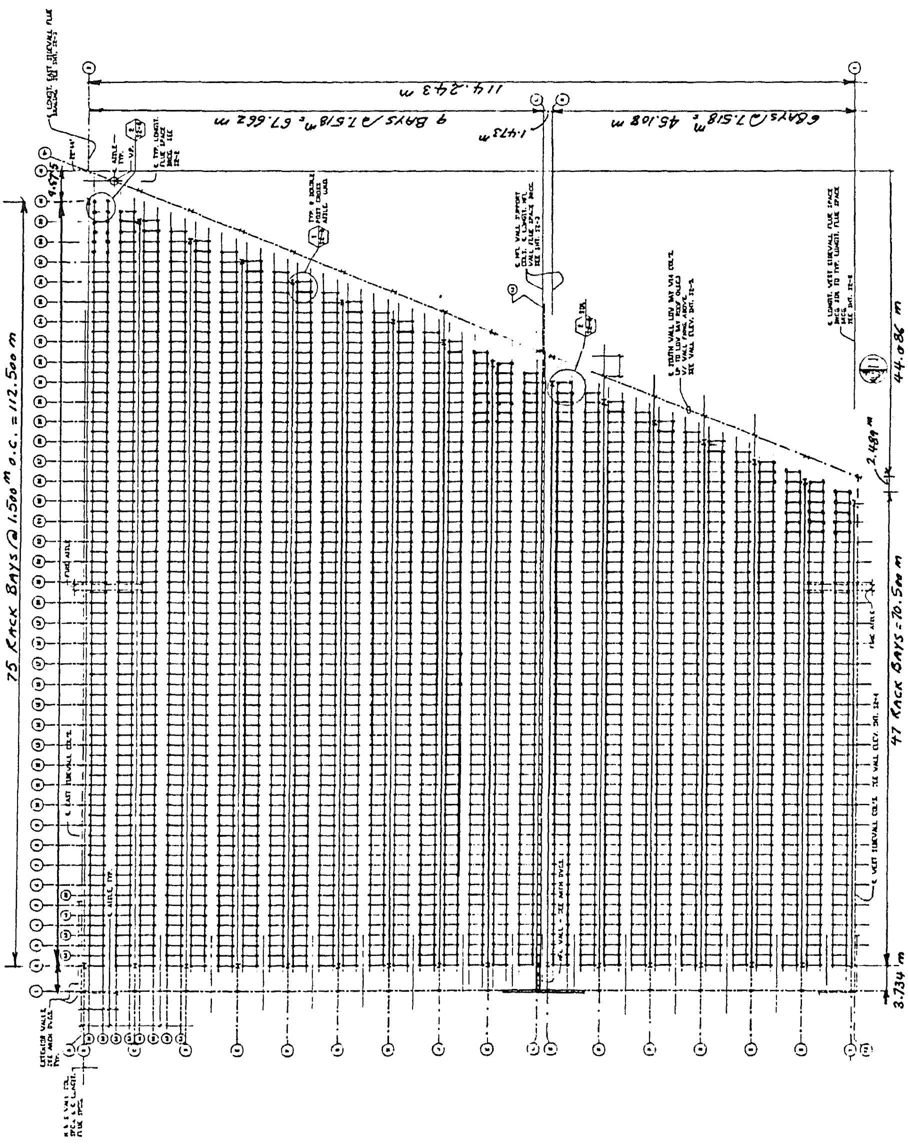
Shop fabrication of the cross-aisle frames in 15 m high section was necessary to satisfy extremely tight tolerances prescribed by operational constraints of the aisle stacker cranes. The 15 m sections of the cross-aisle frames are field welded in an on-site welding jig. A double Vee type of connection splice was used to develop the full tensile capacity of the post thus avoiding heavy stress concentrations at a single plane. This is particularly desirable in the welding of light gauge sections, when their effectiveness is vital in maintaining stability during adverse seismic conditions. Tight erection tolerances also required the use of a separate post baseplate and various size shim plates. Difficulties in the field placement of conventional anchor bolts, mandated the use of high tensile "Super-Kwik" bolts and a baseplate template. This in turn, required accurate placement of top steel reinforcement in the floor slab. Only a 1% re-bar interference problem was experienced during the course of construction.

Typically, horizontal braces are of 50 to 65 mm diameter light gauge pipe construction. Of particular concern was the use of the commonly-used, but economical, flattened end condition to effect a single shear connection. The double lip flattened pipe condition proved satisfactory in a pre-fabrication tension and compression strength test, although this end condition did govern the ultimate strength capacity of the pipe.

Down-aisle braced frame members are all of field-bolted construction. Individual members are bolted in place. Insofar as the 30 m high cross-aisle frames are unstable prior to the installation of these down-aisle frame members, temporary down-aisle oriented erection guys were needed initially to provide the necessary staying.

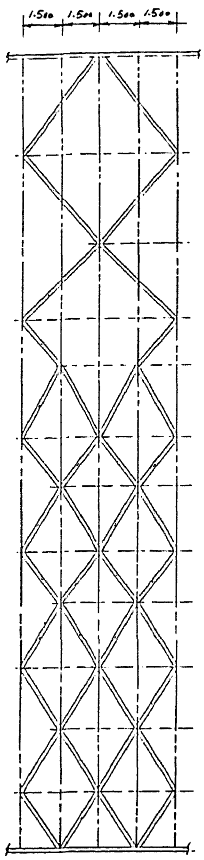
CONCLUSION

The case-study described herein indicates that the construction of high bay automated storage rack-supported buildings of this type is feasible and cost-effective, even at highly seismically-active site locations. In this case, a 30 m high pallet-rack storage facility extending over 11,000 square meters and accommodating ~57,150 pallets has been designed to withstand anticipated, but adverse seismic conditions with little or no construction cost premium over one designed in accordance with the minimum seismic provisions set forth in most current building and industry codes. Construction has entailed the fabrication of 4,000,000 kg of structural steel at a cost of slightly less than $2.00/kg, inclusive of installation.

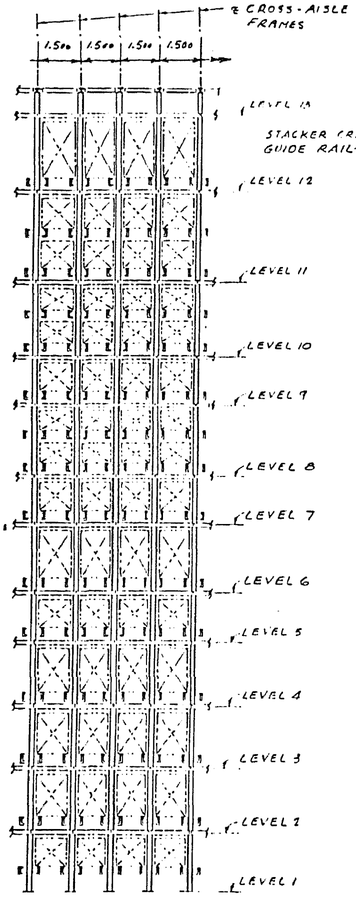


FLOOR PLAN

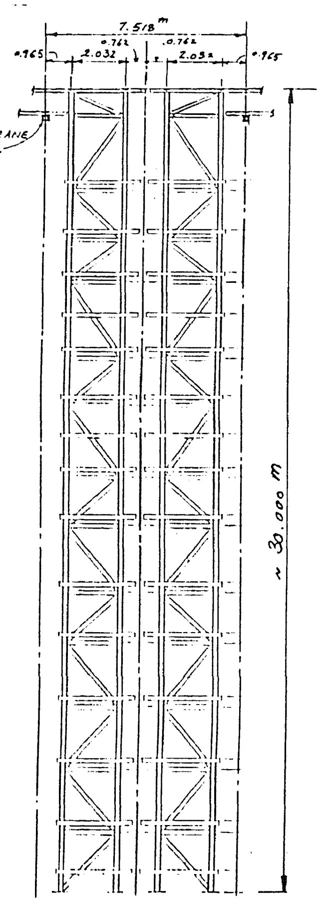
PLATE I



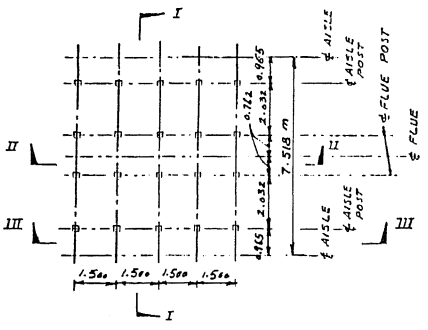
SECT. II - II
DOWNAISLE FLUE BRACING



SECT. III - III
PALLET STORAGE



SECT. I - I
CROSSAISLE FRAMES



TYPICAL FOUR (4) BAY MODULE
PLAN VIEW

PLATE II