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BEHAVIOUR OF STEEL PALLET RACK STRUCTURES UNDER EXCEPTIONAL LOADING CONDITIONS

Partial Report

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Liège, 25.09.2000

CONTENTS

2. NUMERICAL FINITE ELEMENT MODELLING OF RESISTANCE AND STABILITY BEHAVIOUR OF PROCTER AND GAMBLE STRUCTURE UNDER STATIC LOADING AT AMBIENT TEMPERATURE

1. STEEL STORAGE RACKS

1.1 Introduction

The actual philosophy of manufacturing production is no longer that the warehouse is the place where raw materials and finished goods are deposited at either end of manufacturing process, but that storage of the materials for manufacture and of the completed article is an integral component of the manufacturing process. The warehouse becomes the place where elements of production in various stages of manufacture may reside for short or long periods, being recalled and redeposit a number of times, in accordance with the demands of the production process and of the market place.

This view of warehousing has led to the development of complex warehouse systems in which not only the product or component is held pending the next stage in the production operation, but also may be sorted or packed or otherwise prepared for despatch to the customer. In order to meet the needs of the production process, the warehouse and its racking systems must be organised in such a way that the product is efficiently stored and is sufficiently accessible. To meet the former criterion, racking and shelving systems have been designed that make the most cost effective use of space, have adequate factors of safety against structural collapse and are built to tolerances which are small enough to allow the operation of the computer controlled automatic handling equipment. To meet the latter criterion, storage structures of different types have been designed, from simple static shelving systems which are hand loaded, through mobile racking systems in which the racks and its contents are physically moved to provide access, to high bay pallet racks structures perhaps more than 30 m high, serviced by computer controlled mechanical handling equipment. A typical steel storage system is shown in Figure 1.1 [SZA99].

1.2. Typical storage racking systems

Storage racking solutions can be different from many points of view, such as storaging procedure, reside period of the product, handling equipment, etc., but for designers the most important problem is the constitutive structural system of the storaging concept. In the below are presented some of the most common racking systems.

1.2.1. Selective pallet rack system

Storage racking systems range from the simplest shelving structure a few meters high and two or three bays long, hand loaded with relatively light produce, to rack clad buildings more than 30 m high, served by automatic cranes and storing heavy mechanical components or bulk materials. Between these two extremes, the adjustable pallet rack is the workhorse of industry, extended to perhaps 6m high, served by manually operated fork lift trucks, reach trucks, or order picking machines, and carrying typically 2 tone's per beam level per bay. An example is shown in Fig. 1.2 [CLY].

Available in 'wide', 'narrow' or 'very narrow' aisle formats, pallet racking is the most popular and widely used of all heavy-duty storage systems. It is easily installed and highly versatile, with direct accessibility to each individual pallet. All kinds of palletised and non palletised loads can be accommodated. Racking can be adapted to a cater for changes in the type or size of goods stored.

The choice of wide or narrow aisle format depends on many considerations, including the type of goods stored, speed of throughput, accessibility, type of trucks in use and, most importantly, the amount of floor space available for storage.

In this type of installation it is normal for the racks to be placed back to back, each being served from its adjacent aisle. In the down-aisle direction the stability of the structure depends solely upon the strength and stiffness of the beam to column connection. Structures of this type are sometimes strengthened by the addition of spine bracing in the vertical plane between the racks, when the stiffness of the beam to column connection is not adequate to ensure stability. Plan bracing must be then introduced at each level to control the uprights in the front face of the rack [GOD]. In the cross-aisle direction, stability is provided by bracing, which may be welded or bolted to the upright.

1.2.2. Shelving system

The adjustable pallet rack is the most common type form of storage racks in use, but lighter, hand loaded, shelving systems are also common. These likewise often comprise perforated upright sections, but the connection to the shelf is a clip, or hook, which provides little or no restraint to the upright, so that overall stability must be provided by some other system. Commonly this is either bracing or flat cladding sheets, riveted, bolted or clipped into place. The shelf in such cases is a pressed steel component suitable perforated to accept the clip and other connections. In hand loaded shelving system the unit loads do not normally exceed 25 kg. Fig. 1.3 shows a typical example [GOD91].

Clip-type shelves save up to 80% of installation time. They can be used in multi-tier applications with access stairways and catwalks. Clipe-type shelves are easily moved when inventory requirements change.

Multi-tier or mezzanine shelving is possible to construct on two or three levels high (even higher if required and spaces permits). High-rise shelving is an excellent way to provide vertical space utilisation and increased labour productivity.

1.2.3. Cantilever racks

Cantilever racks present no vertical obstructions. Therefore, they are useful for storing long objects. Typical loads are metal extrusions, steel bars, tubes, pipes, furniture and other long items. Figure 1.4 presents an example of such structure [CLY].

The engineers must design arms and columns according to load size and weight, and ensure the correct allowance for vertical clearance and other important factors. They must also advise on guide rails and entrance guards, to protect equipment and product.

1.2.4. Mezzanines

The key benefit of a mezzanine is the ability to create new space fast and efficiently. Mezzanines help to maximise the total cube of area of your facility as an alternative to a costly building addition or even as an alternative to moving premises.

Mezzanines make use of vertical space, which would otherwise go unused. It can convert the space into usable storage, production or office area at a fraction of the cost of a new construction. Usually the mezzanines are totally modular so they can easily be altered or moved as circumstance change.

It is important that mezzanines are designed in accordance with local building code requirements. The designer's experience allows to meet these requirements with minimal customers budget. A typical mezzanine structure is shown in Figure 1.5 [KOR].

1.2.5 Drive-in and Drive-through system

Pallet racking and shelving systems allow comparatively efficient use of floor space combined with direct access to every item in the store. In some circumstances, however, convenience of access to the stored product can be sacrificed to gain more efficient use of space. In such cases, Drive-in and Drive-through racking systems are used. The pallets are supported on rails, which rest on cantilever arms fixed, often by a boltless connection, to the upright. The rack may be of pallets deep, and is serviced by a fork truck which drives inside the structure to place or retrieve its load. In Drive-in rack, the fork truck can gain access from one face only, but in Drive-through racking, as its name implies, the truck may drive through the rack from one face to the other, allowing access from either end. The configuration of this type of rack is shown in Figure 1.6 [PREF][PAL].

Drive-in systems rely for their stability on the base fixity of the upright connection to the floor and on the stiffness of the transom and its connection with the upright. This is supplemented by the stabilising effects of bracing in the vertical plane at the rear of the rack. The effect of this bracing is transmitted to the uprights at the front of the rack by plan bracing over the top, but in deep racks of this kind, the effectiveness of such bracing systems is diminished at the front of the rack. In Drive-through racking no such bracing can be allowed, because it denies access to fork trucks. In such cases the rack stability is desired from the floor fixity and portal frame action alone. In Fig. 1.7 the two types of racking are sketched to illustrate and contrast the basic features of each. [GOD91]

The drive-in system include 60%-80% increase in storage capacity through the reduction in the number of aisles required. The design of this kind of equipment requires much the same information as for standard pallet racks. Detailed specification of the forklifts being used is also needed because the rack bay opening and first tier must provide space for the lift truck and the pallet load.

1.2.6 Push-back racks

Push-back racks offer the same storage density as drive-in/drive-thru racks but greater selectivity. It allows pallets of varying types and sizes to be stored together, two, three or even four deep, with quick and easy access.

Pallets are loaded in sequence onto wheeled carriers or cradles of varying heights, which are 'pushed-back' on inclined steel channels to utilise the full depth of the racking, as shown in Figure 1.8 [STE]. All loads are stored and retrieved from the aisle. Loads in each lane rest on a cart on a rail that slopes gently toward the front. When a new load is deposited into a lane, it 'pushes back' the one already at the face and all those behind. Then, when that load is picked, the contents of the lane all move gently forward again.

The result is to eliminate honeycombing or empty pick faces. Obviously the ideal application for push-back racks will be where all loads in a lane are identical and first-in/first-out stock is not crucial.

Push-back is suitable for all types of pallet load, including in some cases inferior quality pallets, and is particularly suited to operations where space utilisation is permanent - in cold stores, for example.

1.2.7 Flow racks

These are similar to push-back racks except that loads are generally deposited on one side and flow gently to the other, as shown in Figure 1.9 [KOR]. In many ways a flow rack is like a conveyor within a rack structure.

Flow storage consists of two elements, a static rack and dynamic flow rails, a track/roller system set at a decline along the length of the rack. The flow rails allow loads to move by gravity from the loading end to unloading end. Each flow lane includes self-energised speed controllers (brakes) to gently control the speed of movement within the flow lanes. As a load is removed, the loads behind it move forward to unloading position.

Flow racks are used for both cartons and pallets. The flow system depth, height, and width are limited only by size of building facility and the capabilities of material handling equipment. They may be many units deep. Most applications are where the carton or pallet at the front is going to be picked from, and the ones behind are reserve storage.

By achieving High-density, dynamic storage, flow racks offer excellent payback.

1.2.8 Choosing the right rack system for a given application

Maximize storage efficiency and cut operating costs are the goals for any investor. There are different studies on choosing the right rack system [OLI97].

As show previously, there are a variety of configurations for storage rack, all which achieve a different level of selectivity and storage density. The classic selective pallet rack system provides 100% selectivity to every load, with access to every pallet. However, they require numerous aisles and result in lower storage density than some other alternatives [STE].The storage systems are operated by human handling systems (as forktrucks, forklifts, etc.) or by automated systems. For low-rise racks the first ones are generally utilised. The automatic devices operate mostly to high-rise racks.

For faster moving product, and the best access, selective racks are the system of choice.

If benefit can be taken from bulk storage and it is not necessary to handle a wide variety of palletised loads, then drive-in and drive-thru racks can bring important efficiencies and economies. These systems offer greater storage density than selective racks, but less selectivity.

For items that will have longer life in storage, and don't require immediate access, drive-in systems are an excellent solution.

Experience shows that drive-in rack maintenance costs an average of 4% of the original purchase price. Push-back rack is heavy duty and therefore has very little damage. A push-back system provides 3 to 4 times the selectivity of drive-in racks by allowing each level to store a different product. Push-back reduces aisle width previously required to support forktruck scissors, for another storage systems, as shown in Figure 1.10 [ADV].

1.3. Special storage racking systems - rack supported building

Rack supported structures are used by many companies to solve their expansion needs for as much as 40% less than the cost of a free-standing building of the same size [UNA]. The savings come from the elimination of steel columns and long span roof trusses plus the reduction in size of supporting members, because the rack structure has columns on much closer centers. By eliminating those building columns and long span roof trusses, the building dimensions are substantially reduced for an equal number of units stored. This is especially important to land-locked companies whose only answer to expansion is a high-rise, high-density storage structure, as shown in Figure 1.11 [TRA].

There is no limit to how high the structure can be built other than local zoning regulations.

High - rise rack supported buildings storage systems are operated by automatic systems. For such storage buildings, the most suitable rack system operated by automatic system is the selective pallet rack, due to its selectivity and easy access to every pallet.

There are many companies around the world which produce rack storage systems but only a small part of those companies deal with rack supported building systems, due to the complexity of the structure. Some of the firms with experience in producing this particular type of rack structure are given in the references [ENG][FRA][PRES][UNA][UNI][TRA].

1.4. Storage racking component members and design

1.4.1. Definitions

Storage racking is an area which forms a significant outlet, perhaps 20% of all the constructional use of cold-formed sections, and utilises a substantial proportion of perforated members. [RHO91]

For selective storage pallet racking system , as shown in Figure 1.12 [PREF] generally the beams have boxed cross-sections while columns present perforated open sections to accept the hooks of the beam end connectors, which join beams and columns together, without the need for bolts or welds.

The upright columns of steel storage racks are generally manufactured from channel members. In accordance with USA practice, bracing members are welded to the uprights so that simple lipped channel is used. Otherwise, in Europe and Australia, additional flanges (called rear flanges) are attached to lips to allow bolted braces to be connected to the uprights. In some cases, additional lips are located at the ends of the rear flanges and normally point outwards.

As shown in Figure 1.12, bracing systems are generally placed only in the cross-aisle direction. Due to the need to organise racking system in such a way that the product is efficiently stored and sufficiently accessible, the presence of bracing systems is generally hampered in down-aisle direction, and lateral stability is hence provided by the degree of continuity offered by the beam-to-column joints and base plate connections. [BAL98]

Typical configurations of pallet racks are shown in Figures 1.13-1.16. The configuration of a typical unbraced pallet rack is shown in Figure 1.13 and a more detailed example in Fig. 1.14, in which the down-aisle stability is provided solely by the restraining effect of the beam end connectors. In the cross-aisle direction, stability is provided by the bracing in the frames which, in the case of double entry rack shown, should be linked together in the height by frame spacers.

For the braced rack shown in Figures 1.15-1.16, down aisle stability is provided by spine bracing in the vertical plane at the rear of the rack. The stabilising effect of the spine bracing is transmitted to the unbraced uprights at the front of the rack by means of plan bracing.
Racks may be braced over only part of the height in which case they require special consideration.

Referring to Figures 1.12-1.17 and in addition to the definitions used in [HAN98] and [EUR94] the following supplementary definitions for the component members of storaging systems are used in [AUS93] and [FEM97]:

- **adjustable pallet racking -** storage system comprising upright frames perpendicular to the aisles and independently adjustable, positive locking shelf beams, spanning between the frames parallel to the aisles, and designed to support unit loads
- **aisle width** - space along which the unit load handling equipment operates

- **base plate** - bearing plate bolted or welded to the underside of the column to transmit vertical and horizontal forces into the floor, and provide structural fastening of the upright frame to the floor
- **basic material** - flat steel sheets or coiled strip from which the rack components are pressed or rolled
- **batch of steel** - quantity of steel, all to the same specification, purchased from one supplier at one time
  bay load - the sum of the compartment loads in one bay of the structure, not including the weight of any goods stored on the ground.
- **bay height** - maximum vertical distance from the ground to the highest point of the unit load in a racking structure
- **bay width** - see definition of shelf beam length
- **beam** - a horizontal member linking adjacent frames and lying in the horizontal direction parallel to the main aisle
- **beam end connector** - connector, welded to or otherwise formed as an integral part of the beams, which has hooks or other devices which engage in holes or slots in the upright.
- **ceiling clearance** - minimum vertical distance between the highest part of the upright frame or the highest part of the unit load on the top shelf beam level and the underside of the ceiling or the support steelwork for ceiling
- **closed-face racking** - adjustable pallet racking where the unit loads are supported by the shelf beams (Fig. 1.17a)
- **columns** - vertical members that comprise the upright frame and are subject to compressive forces parallel to their longitudinal axes and have provision for random attachment of shelf beams
- **column protector** - component in front of the upright frame that is secured to either the floor or column, or both and designed to resist minor impact
- **column width** - maximum horizontal distance of an upright frame column measured from flange to flange
- **compartment load** - the load which can be loaded into one compartment of a rack or shelving structure from one side
- **diagonal brace** - diagonal member in the vertical plane to supplement horizontal braces to join columns together and form a trussed upright frame that is rigid and stable, and designed to withstand applied design loads
- **finished tolerances** - tolerance of the unloaded racking after fabrication and erection prior to initial loading
- **fully automatic operation** - operation of machines by fully remote controlled robots without manual interference
- **horizontal brace** - horizontal member that joints two columns together in an upright frame by bolting or welding
- **manual operation** - operation of machines and positioning of equipment controlled by an operator
- **open-face racking** - adjustable pallet racking where the unit loads are supported by stub arms attached to the columns (Fig. 1.17b)
- **operating clearance** - nominal clearance dimension between static and moving parts to ensure safe operation
- **perforated member** - a member with multiple holes regularly spaced along its length.
- **row length** - maximum horizontal length of continuously connected bays in a racking structure and is the sum of column widths plus bay widths

- **row spacer (bracktie)** - horizontal member, usually bolted to upright frames to maintain distance between upright frames in a double-sided racking layout and designed to resist applied design loads, and provide moment connection between racking, and rigidity to the structure (Fig. 1.18)
- **shelf beam** - horizontal member securely locked into the upright frame by means of shelf beam connectors and designed to support vertical loads and resist horizontal loads
- **shelf beam connector** - device welded to the shelf beam ends, secured by means of patented boltless connections or bolted to upright frames and designed to transmit forces into the upright frames and provide stability within the racking structure
- **shelf beam deflection** - maximum vertical distance measured from the beam ends to the lowest point of the beam in a loaded condition
- **shelf beam height** - vertical distance from the top to the underside of the shelf beam
- **shelf beam length** - horizontal distance between the inner faces of columns in adjacent upright frames (this dimension is needed to conveniently manoeuvre pallets into a bay taking into account unit load width and minimum clearances required)
- **shelf beam safety device** - usually patented positive locking device, secured to the shelf beam connector to prevent dislodgement of the shelf beam from the upright frame when subjected to upward forces
- **spine bracing** - sway bracing in the vertical plane parallel to the main aisle of the rack, linking adjacent frames.
- **spring back** - the tendency of a cold formed section to undergo spontaneous cross-sectional distortion when it is cut from a longer length
- **tolerance** - permissible positive or negative variation from nominal dimension or position resulting from either manufacture or erection, or both
- **unit loads** - laden individual pallets or equivalent load modules
  - the weight of an individual stored item, e.g. a pallet or a box or a package on shelving system.
- **unit load clearance** - distance between unit load and racking component
- **unit load column clearance** - maximum horizontal distance from the inside face of the column to the nearest part of the unit load
- **unit load depth** - horizontal dimension of the unit load measured perpendicular to the unit load width
- **unit load depth clearance** - minimum horizontal distance between adjacent unit loads in a double-sided racking situation
- **unit load height** - maximum height measured from the underside of the pallet to the highest point of the unit load
- **unit load height clearance** - minimum vertical distance between the highest point if the unit load and the underside of the shelf beam
- **unit load overhang** - maximum horizontal distance the unit load protrudes beyond the outer face of the racking
- **unit load width** - horizontal dimension of the unit load measured parallel to the operating aisle
- **unit load width clearance** - minimum horizontal distance between adjacent unit loads on a common shelf beam
- **upright** - vertical member (column) of the upright frame
- **upright frame** - vertical frame assembly composed of uprights and bracings to support design loads transmitted through shelf beams and operating equipment - two (often perforated) upright sections linked together by a system bracing or batten members.

Upright frames lie in the vertical plane, in the cross aisle direction, normal to the main aisle of the rack. Typical examples are shown in Figure 1.20.

- **upright frame height** - maximum vertical height of an upright frame assembly including baseplates and packing plates (when required)
- **upright splice** - vertical member used to splice two columns together to form a composite column and designed to support vertical loads and resist horizontal loads
- **vertical clearance** - minimum vertical distance between the floor and the underside of the lowest shelf beam; or minimum vertical distance between the top of the lower shelf beam and the underside of the upper shelf beam
- **wall tie** - horizontal or vertical member that connects the upright to a wall (or ceiling) to provide stabilizing forces and reduce overturning moments (see Fig. 1.19)

1.4.2. Pallet rack beam sections

The most common forms of beam section for pallet racking system are the boxed beam and the open beam. Examples are shown in Figure 1.21. The box beam is made up of two interlocking lipped channel sections which are both welded at their ends to the beam end connector. Although the beam comprises two open sections which are themselves not symmetrical about the vertical axis, and which exhibit torsional-flexural behaviour under vertical loading, the effect of interlocking the two is to suppress the behaviour of the individual components and to provide a beam section which has the well behaved properties of a full box section. For normal range of horizontal spans, the beam is limited by its bending capacity, and failure occurs as a local compression failure of one of the flanges of the channels. This failure, in practice can only occur where there is no normal pressure from the loads preventing the local buckle from developing. The most common configuration for beam loading is that shown in Figure 1.22 with two pallets in place. Buckling of the beam is only possible between the pallets.

The box beam is generally more efficient in its use of material than open beam shown in Figure 1.21 because there is relatively a greater concentration of material in the flanges where it is most needed. However, for lighter loads, the open beam section becomes economically more attractive, its reduced structural efficiency being offset by saving in assembly costs. In addition this section can be stepped in the manner shown in Figure 1.21c to provide a location for shelves and other components in the system
Lateral stability of boxed beams is not usually a critical factor in the design of the section, but other sections, especially those such as the stepped channel section, do twist under load, and for the longer spans, ties are commonly fitted between front and rear beams in the rack to reduce this effect [GOD91].

1.4.3. Pallet rack upright sections

In the early days of the development of pallet racking systems, upright sections were nearly always simple lipped channel sections. This shape was also available from cold roll section manufacturers in arrange of sizes, and because of the limited number of bends, required relatively simple sets of rolls in its manufacture. However, developments in the industry acknowledged the need to consider not simply the upright in isolation but the frame as an assembly in assessing costs and efficiency. The lipped channel itself was cheap to manufacture and structurally efficient, but its shape made it difficult to make connections to bracing elements in a neat and effective way. When hot-rolled material was used, welding provided the best solution, but one not available to those manufacturers using cold rolled material, who had to adopt a bolted arrangement. This involved spacers to avoid the lipped flange, thus reducing the effectiveness of the bracing, and did nothing for the appearance of the product in an increasingly sophisticated market.

Consequently, new sections were devised, and typical is shown in Figure 1.23, which has extra bends and provides for a simple bolted connection to the bracing elements. The shape of this relatively complex section is therefore determined by consideration of ease of assembly as well as that of structural efficiency.

In normal pallet racking structures, all upright sections are perforated to accept the hooks of the beam and connector from which is the heart of the structural system. Usually these are two parallel rows of perforations to accept a connector from each side of the upright, but in some systems, especially the lighter ones, a single row of slots accepts both connectors. In addition to this, further rows of perforations are provided in the rear tails of the section, to accept the bracing connections.

For high - rise rack supported building structures, operated by automatic systems, usually the external beams of the selective rack are also rails for the pallet transport devices. In these conditions, the beams are continuous lipped channels with bolted or welded connections to the uprights. These uprights have perforations only for the bolted connection case, near the joints, in order to put the bolts.

The very lightest racking systems are free standing on the floor of the warehouse, factory or office, with no fixings to the floor. Base plates tend to be thin pressed components, except for on the heaviest racking structures, and fixing of at least the front uprights of a pallet rack, by one bolt each, is fairly standard. Increasing frequency of fixing and heavier baseplate arrangements are introduced as the payload increases. Figure 1.24 shows a typical standard duty pallet rack baseplate.

Baseplates are fitted to uprights to spread the loads into the floor. Normally these are simple thin flat plates, perhaps 3 mm thick, which are bolted to the upright and to the floor. Grouting underneath the baseplates is not normally employed, and levelling of the column is achieved by the addition of levelling plates or shims underneath the baseplate. The floor fixing is with a single bolt, which is of the expanding type to provide some resistance to uplift. In most standard pallet racking installations, however, no attempt is made to improve the fixity of the base by the addition of more holding -down bolts or thicker baseplates. Thus, the condition of support at the end of the upright is that it is restrained in position by a single holding down bolt, whilst any directional restraint occurs primarily from the "lat end" effect.

The foregoing is true for normal adjustable pallet racking. Improved base fixings are provided for taller supported building racking systems and are absolutely necessary for drive-in and drive-through systems, where the stability of the complete structure is highly dependent upon the rigidity of the portal connection at the top of the column and the degree of fixity at the base of the column. In such cases a thicker, heavier baseplate is welded to the column and at least two bolts are fitted, on either side of the upright, to provide some moment capacity [GOD91].

Resent researches concerning the behaviour of pallet rack systems are focused on the stability behaviour of the cold-formed steel beams with opening, in order to develop simple design recomendations [LAB97][SZA99].

The European standard for the design of static pallet racking [FEM97], provides recomendations for the tests on floor connections, in order to evaluate their resistance and the rotational rigidity.

1.4.4 Beam end connector

The connection between a column and a beam can be classified into fixed, pinned or semi-rigid. A semi-rigid connection possesses intermediate elasticity and the joint is normally formed by the use of bolts or welding.

In the storage racking industry, for normal selective pallet racks, boltless semirigid connections are used. They referred to as beams and connectors and use tabs as connectors. The tabs are engaged into perforations of cold-formed upright sections at optional heights determined by a perforation pitch. The tabs may be an integral part of the beam end connector, or may be independent from it, at which point they are referred to as studs.

A cold-formed, boltless, semi-rigid beam end connector may be considered to be analogous to the bolted end-plated semi-rigid connections used in heavy structures. The tabs or studs, which provide the interlocking arrangement, perform the same function as that of bolts in semi-rigid structural joints. The end plates are subjected to the same loading conditions as those of other structural joints.

There are many types of such joints. A typical as for example is shown in Figure 1.25. The beam end connector, during use, makes contact with the upright's web and flange. All the beam end connectors are locked with devices which guards against accidental uplift.

Beam end connectors are made from hot-rolled material, which is selected, for its forming properties as well as for its structural performance. In addition it must be weldable material.

The behaviour of the beam end connector is crucial to the behaviour of the system as a whole. Its role is to provide a means of supporting the beams, and in addition, because of its stiffness, it restrains the uprights. Unbraced racks rely for their down-aisle stability on the stiffness and strength of the beam end connector alone. The beam end connector provides a semi-rigid connection between the beam and the column. The behaviour of the connector cannot be effectively predicted by any modelling approach and so tests are made to establish its performance. The European Recommendations [FEM97] for the design of static pallet racking, provides informations about the tests on connections in order to evaluate their rigidity. Recent researches [MAR97] provides a formula for the rigidity of some typical boltless connections used in storage rack industry, based on experiments.

The high - rise rack supporting building structures are braced on the down-aisle direction, but the evaluation of the rotational rigidity of beam - to - column connections, usually considered as pinned, by means of tests, numerical studies or by existing literature formulas [ZAH00a] [ZAH00b], may bring supplementary stiffness for the down-aisle direction.

1.5. Fire design of steel storage racks

The presence in the buildings of great quantity of combustible gases represents the main cause of possible developments of fire. The general concept in determining the fire resistance of the structural elements of a building is based on the fact that fire produced temperatures reduce the materials strengths and stiffness until possible collapse. The main requirements imposed in case of fire is that all the existent persons in the building and in the fired compartments have to be evacuated without losses of human life. On the other hand, the losses of the building structure and material goods exposed to fire have to be within acceptable limits.

Taking into account these criteria, the resistance and stability of rack supported building systems must be verified at elevated temperatures. From fire design point of view, the rack systems included in a building with an independent resistance structure are considered only in order to evaluate the fire load density provided by the stored goods.

The fire resistance of a construction depends essentially of the fire load density, exposure time, applied loads, structural system and behaviour of materials at elevated temperatures.

1.5.1. Fire models

The fire development and extension in a compartment in the first phase are influenced by the active protection measure (detection, automatic extinction, etc.) as shown in Figure 1.26 [FUR95]

The fire intensity and development after the flashover phase is conditioned by several causes. The most important are the fire load density and the ventilation. There are several fire models. The nominal model and the parametric model are implemented in standards, as the European Standard for fire design [EUR91]. The other models, more complex and advanced, are one zone and multi-zone models. For these, research is still in progress, but the results obtained until now demonstrates a closer behaviour to the reality than for the nominal and parametric models.

The nominal ISO time-temperature curve, accepted by almost all of the fire standards around the world, does not take into account any physical parameter. As Figure 1.26 suggests, this curve can be far away from. From the beginning, the nominal model supposes that the entire compartment is in the flashover phase and the temperature is increased continuously, without taking into account the cooling phase. In fact, this conventional curve represents the temperature evolution in the first experimental oven built at Columbia University at the beginning of the XX'th century, when railway wood blocks were utilised for energy supply [FRA98].

The parametric temperature-time curves consider some physical parameters as the fire load density, the dimensions of the openings and the thermal properties of the compartment walls. The parametric curves suppose that the entire compartment is in the flashover phase, but takes into account the cooling phase. This model is limited for small compartments. For industrial buildings, with large surfaces, the parametric model is not suitable, because it is far away from the basic assumption that the temperature is homogeneous in all the fire compartment.

For the One Zone model, the temperature in the compartment is still considered uniform and the model is still valid only for the flashover phase, but the temperature-time curve is determined by a more advanced approach, solving the equations of mass and energy of the compartment, taking into account the walls and openings. This model leads to complex calculations and therefore a computer program is needed in order to solve the equations of the system.

In the frame of the ECSC research "Natural Fire Safety Concept" [ECSC] it was considered necessary to develop a computer program of a one zone model. Being part of the Working Group I "Natural Fire Models", the Department Ponts et Charpentes from the University of Liege, take this charge through the fire research team conducted by Prof. Jean-Marc Franssen. This objective is now reached, a computer program called OZone is available in order to determine the temperature-time curve by means of the one zone concept. This program was validated through different fire tests and gives good results.

The use of OZone is not limited to a certain high of the fire compartment, like the parametric model, but it is still limited for the floor surface. However, between all above presented models, the one zone model with a "Fast" rate of heat release is the closest to the basic assumptions, for the case of large surface buildings, and then the most suitable.

For pre-flashover phase the two zones model is suitable. In this model, the fire compartment is divided in a hot upper zone and a cold inferior one, separed by a virtual membrane. For each zone, with uniform temperature, mass and energy equations are solved. Complex equations describe the air movement in the fire plum, the radiative exchanges between the zones and the gas movements on the openings and adjacent compartments. A computer program in which the two zone model is implemented was also developed at the University of Liege.

In conclusion, for high-rise industrial buildings of rack supporting structure type, the two zones model is suitable for the pre-flashover phase and the one zone model for the phase of fully developed fire, for "Fast" rates of heat release. The fire research team of the University of Liege is actually developing a computer program which combines the two models, in order to provide a temperature - time curve which contains in the pre-flashover phase the results from the two zones model and for the flashover and cooling phase the results from one zone model.

1.5.2. Case study on fire behaviour of high-rise storage rack supported building

An interesting approach for the fire design of a high-rise TRAVHYDRO storage rack supporting building [TRAV] was performed at CTICM [CTI99]. The analysed structure is a warehouse operated by automatic systems, built in France at Amiens for Procter & Gamble company. The building has a surface of $9168m^2$ and 30m high. A detalied description of this structure is given in Chapter 2.

The requirement for this building in a fire situation, is that the building may be visited by the firemans on their arrival. That means that, even if a rack of the structure falls down, the entire building must not present a 'chain' collapse.

The active protection measures (detection and sprinklers) allow for a rapid reaction of the fire brigade, in less than 15 minutes. The required time of fire resistance of the structure, before the general collapse is then of 30 minutes, which is sufficient for the firemans to inspect the building and to begin to put out the fire.

In order to realise such study, a fire scenario considering a two-zones model with multiple compartments was considered in CTICM approach. The hot gas spreading between the compartments was calculated on the basis of pressure gradient. For each compartment volume, there are three variables which results from this model:

- temperature of superior layer;
- temperature of inferior layer;
- distance between the two layers.

The stored goods produce a fire load density of 8400MJ/m2 (equivalent of 600kg of wood/ m^2). The fire spreading type was considered "Fast" with a rate of heat release of $500kW/m^3$.

Iterative calculations were made, in order to consider the possibility of a fire extension, the post-flashover phase when the combustible is totally burnt, or the openings in the roof, when locally the fire may be important and create a local collapse under the roof.

With the fire supposed to develop from the middle of the building, as shown in Figure 1.27, a half-structure of 10 cross-aisle rack frames was considered. The structural symmetry was taken into account by introducing appropriated support conditions in the right side of the middle rack, on the horizontal elements which links the racks. The outer-plan displacements are fixed in the intersection nodes of the cross-aisle frame with the rails and internal beams of the racks. The other nodes of the structure are free to move outer-plane; thus, a 3D behaviour of the structure is analysed, even if the cross-aisle frames are considered, only.

After 14 minutes of fire, the inferior part of the middle rack, which is subjected directly to the fire, collapses, by the buckling of the uprights. The collapse of this rack lead to the rupture of the horizontal link elements with the next one, and from this moment this rack is retired from the structure. The other racks, having a lower temperature remain stables. After 25 minutes, the upper part of the second rack losses its stability, as shown in Figure 1.28, and it is retired, too. The analysis is conducted until 35 minutes, without any other collapse, so the conclusion is that the structure fulfil the requirements of 30 minutes of fire without chain collapse.

Despite the complex model of fire, and of the advanced numerical analysis of the structure at elevated temperature, due to the limited time allowed for this study, there are some aspects in which the work may be continued.

First, it is interesting to compare the complex fire scenario of the CTICM study with the Two-Zone and One Zone models. As shown previously, the Two-Zone model may be used for the pre-flash-over phase, while the One Zone model may be used in this case, for such large surface, after the flash-over phase, for a 'Fast' type fire. For this building, of 30m high, it is important to consider the pre-flashover phase by means of the Two-Zone model. One of the aims of the present study is to propose a simplified approach for the fire scenario, by means of this models, using the computer programs developed at the University of Liege.

Concerning the structural analysis at elevated temperatures, a separate analysis of the down - aisle direction is important to be done. In the CTICM model, the rails and the internal beams were replaced with simply supports, which means that the structure is heavy braced in the down-aisle direction. This is not the case for the Procter & Gamble rack structure, as it will be shown in chapter 2 of this study. Furthermore, if the collapse of the structure is produced in the down-aisle direction, it is interesting to know if the rack falls down inside the building or not. A collapse outside the building may affect the neighbourhood, and it is to be avoided, in the same way as a chain collapse in the cross-aisle direction.

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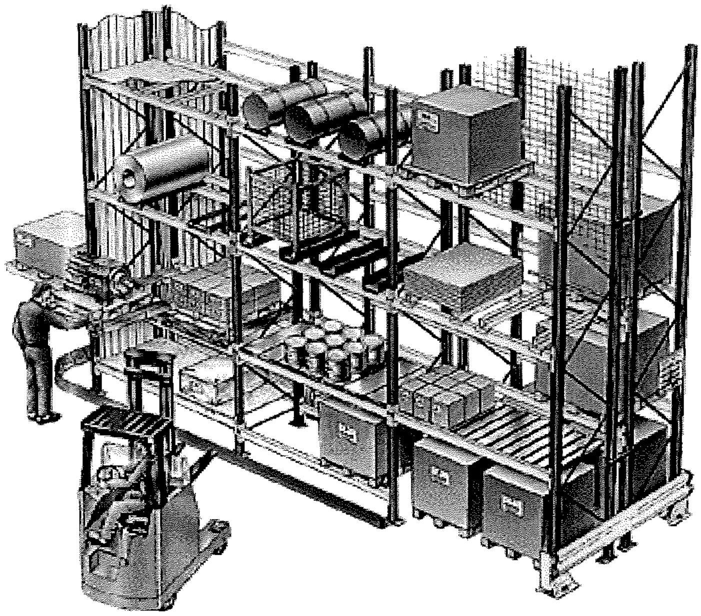


Fig. 1.1 Typical steel storage racking

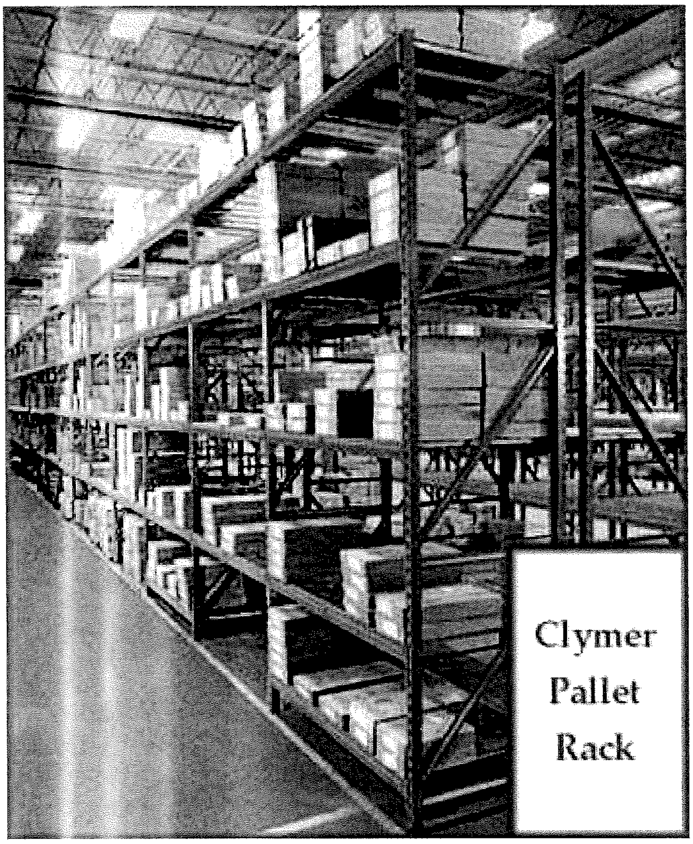


Fig. 1.2 Selective pallet rack

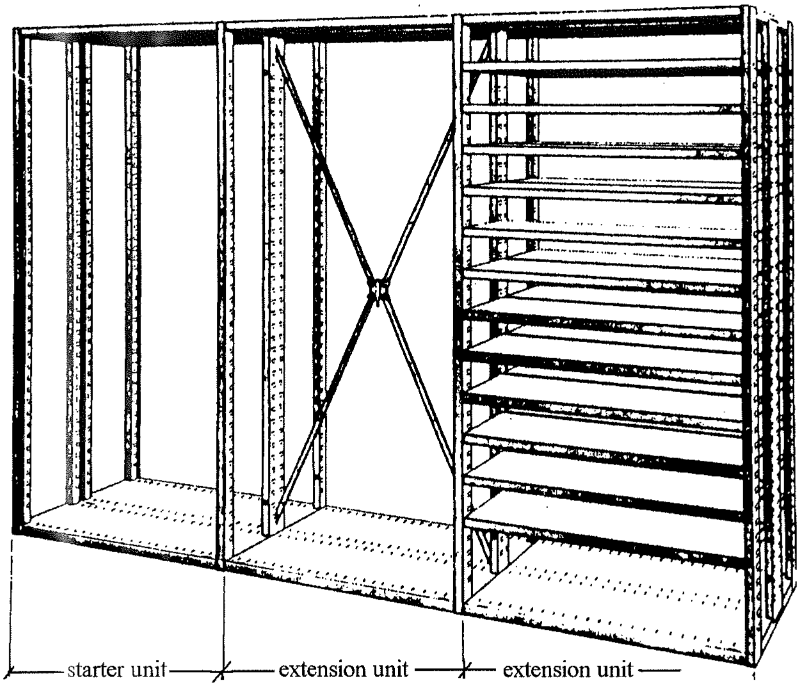


Fig. 1.3 Shelving

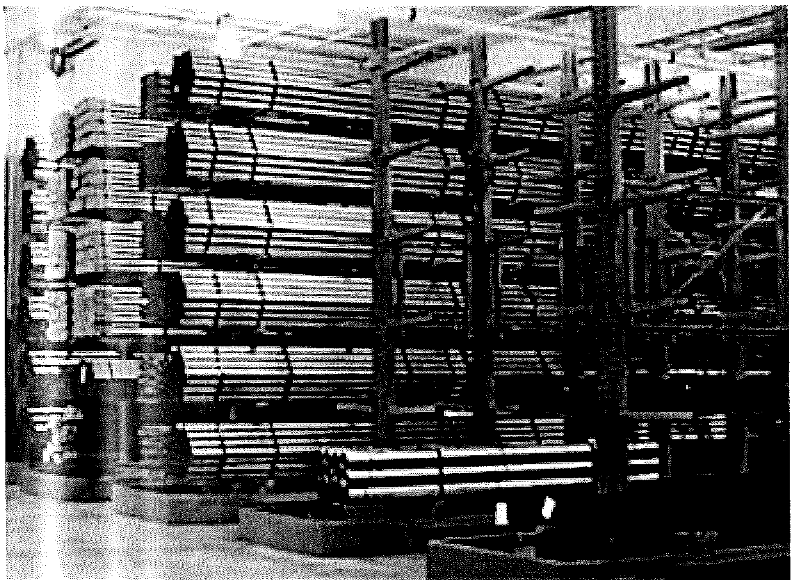


Fig. 1.4 Cantilever rack

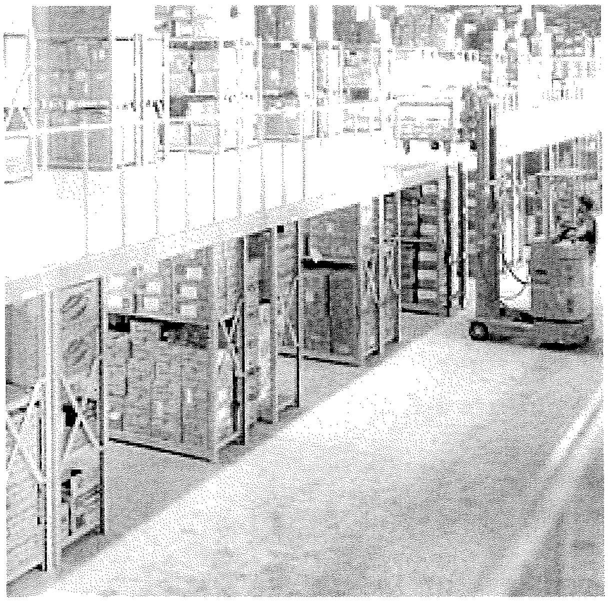
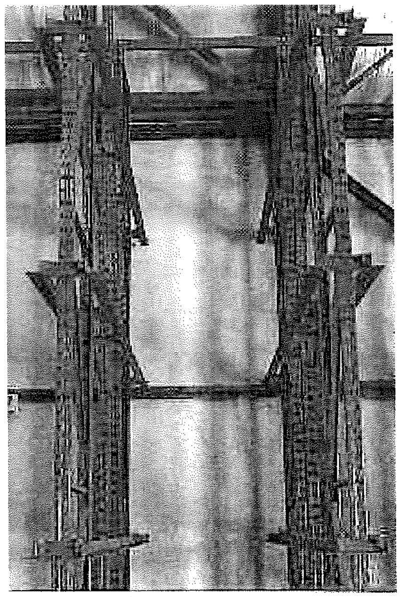
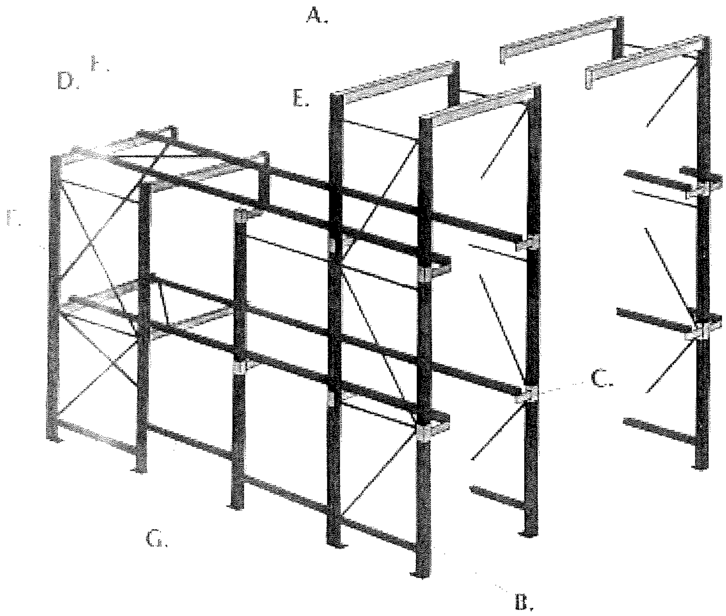


Fig. 1.5 Mezzanine

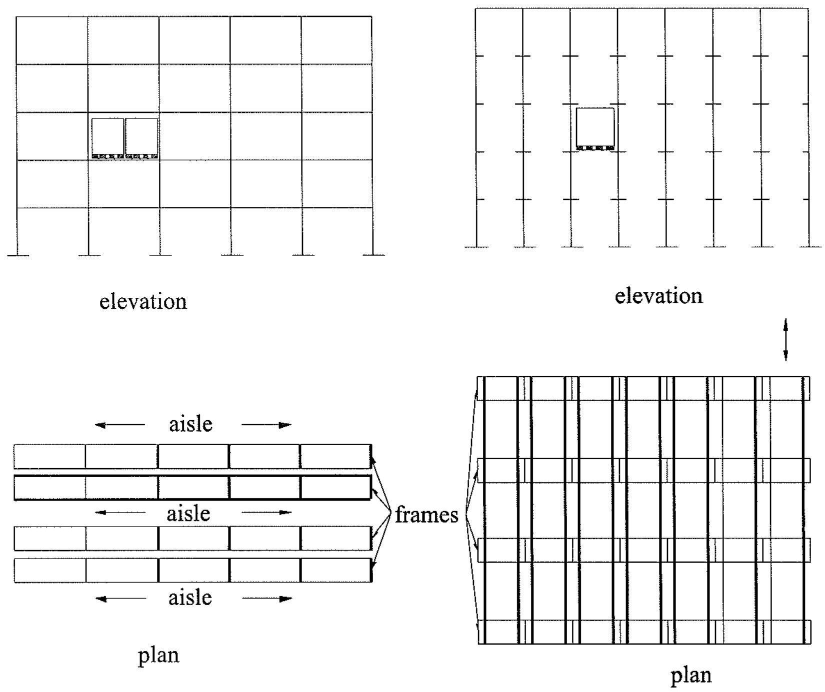


Drive-In & Drive-Thru Racks bring efficiencies & economies.



A. Top tie: Beams provide rack stability at the front of the drive-in system.
B. Rack Upright Frames: Support top ties and rail supports.
C. Rail Support Arms: Pallet rails to support pallets.
D. Rigid Anchor Support Beams: Used in the endbays to enhance lateral rail strength projected to the front of the rack bay.
E. Pallet Support Rails: Placed on channel or angle, hold pallets along row length.
F. Rear Diagonal End Bracing: Placed on the end bays to improve rigidity of the rack rows.
G. Bolted Spacers: Used between uprights to provide correct row length.

Fig. 1.6 Drive-in system



a-pallet rack *b-Drive-through rack*

Fig. 1.7 Typical configuration for pallet and Drive-through rack

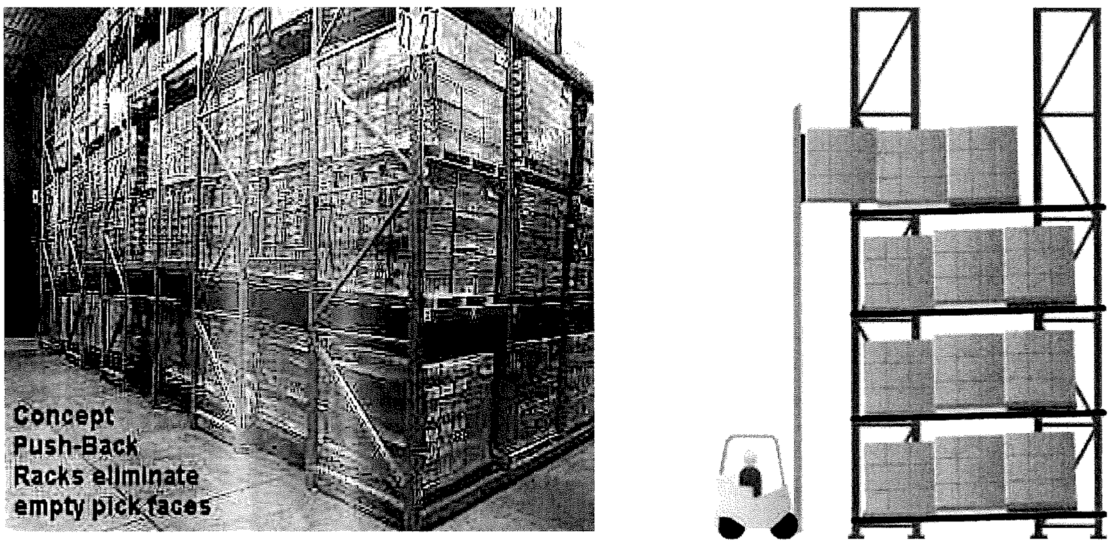


Fig. 1.8 Push-back rack

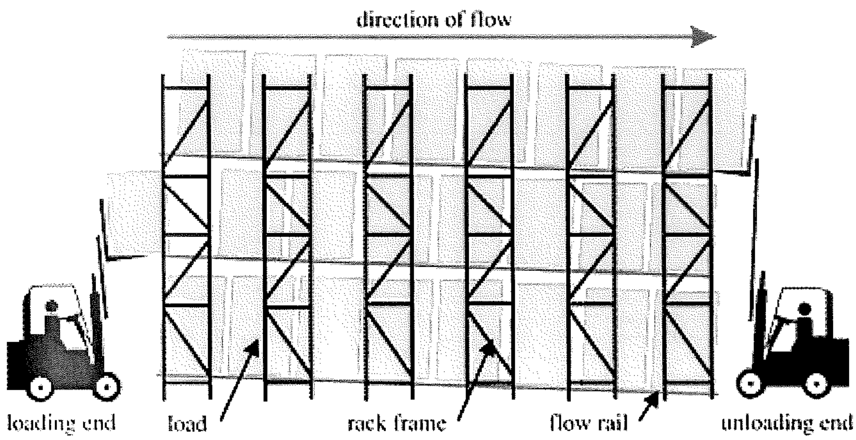
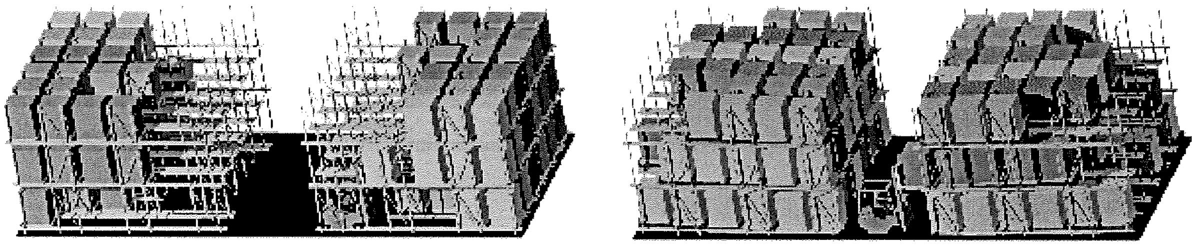
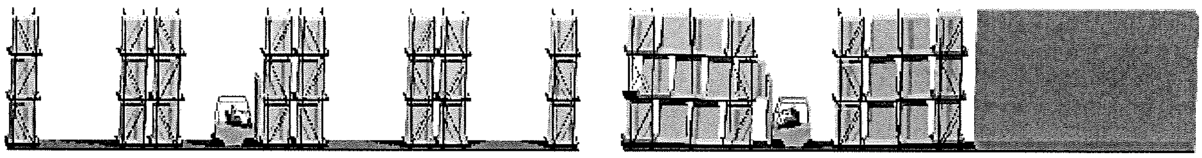


Fig. 1.9 Flow rack



Drive-in versus Push-back



Selective versus Push-back

Fig. 1.10 Push-back system advantages

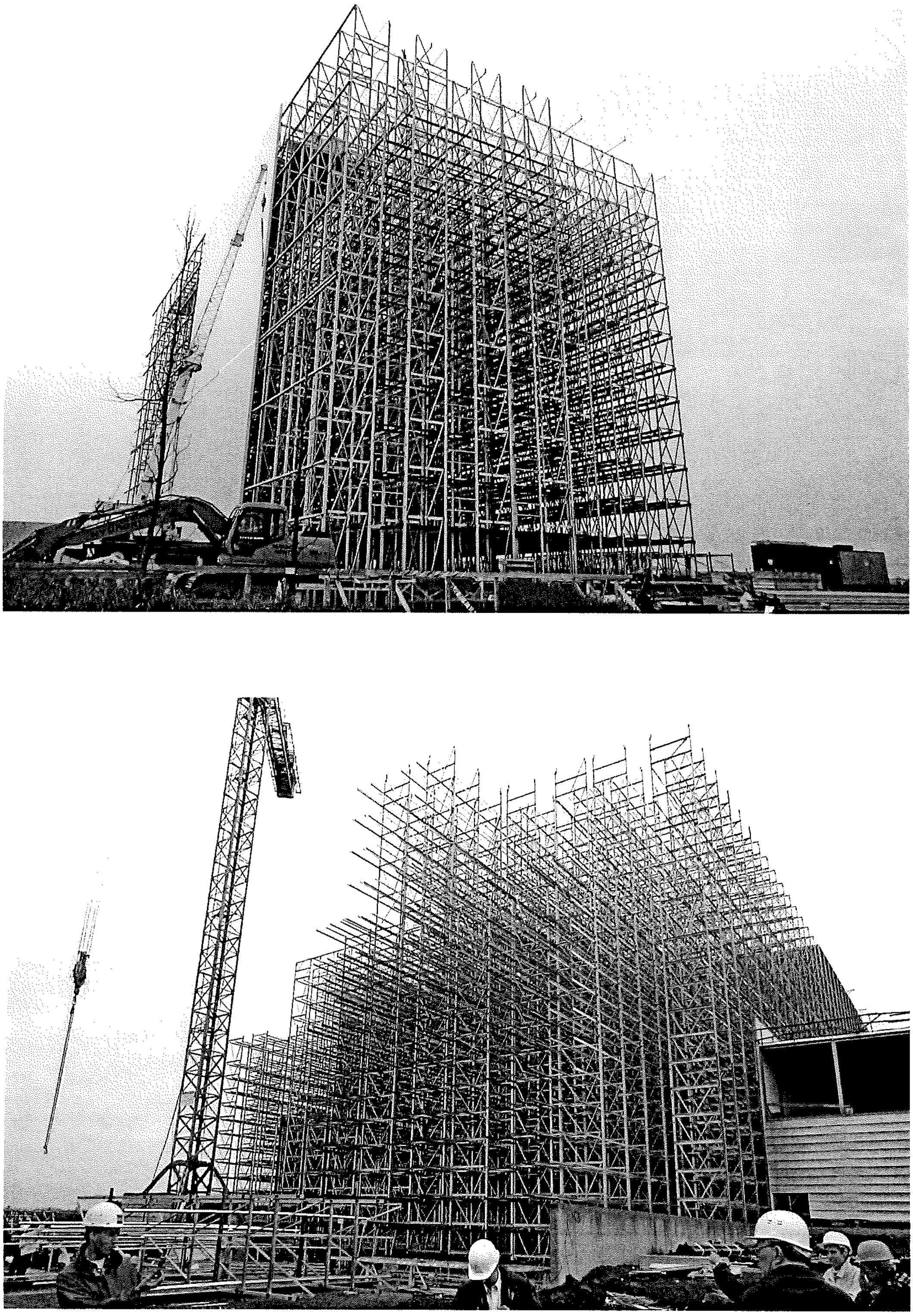
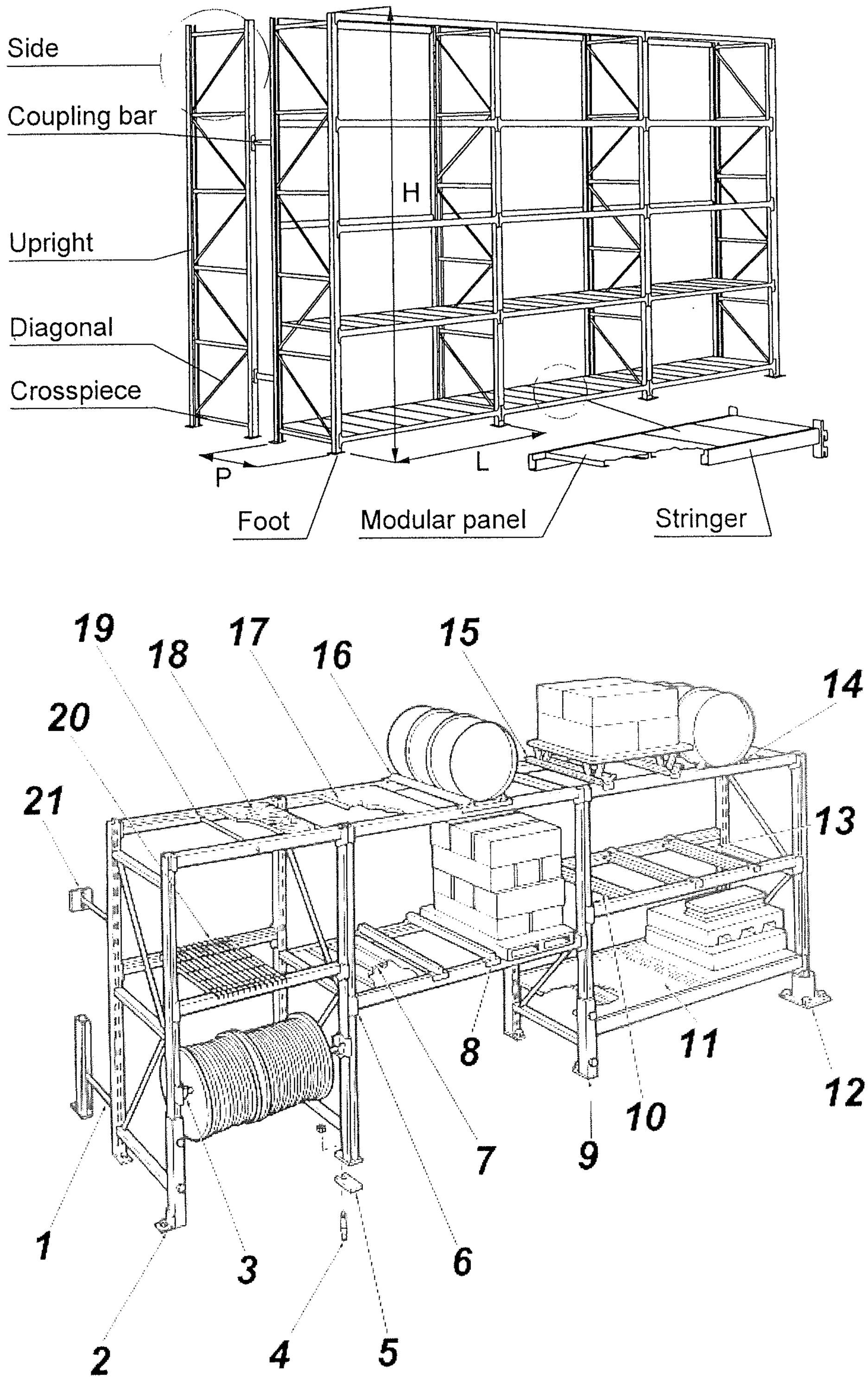


Fig. 1.11. Rack supported building



1. Back to Back Tie 2. Corner Post Guard 3. Reel Holder 4. Concrete Anchor 5. Interlocking Shim 6. Beam Connector 7. Ribbed Steel Deck Panel 8. Fork Spacer 9. Post 10. Pallet Support 11. Solid Steel Deck Panel 12. Deflector Guard 13. 14. Barrel Supports 15. Skid Channel Guard 16. Barrel Cradle 17. Particle Board 18. Plywood Deck 19. Beam to Beam Tie Waterfall Support 20. Wire Deck 21. Wall Tie

Fig. 1.12 Pallet racking system components

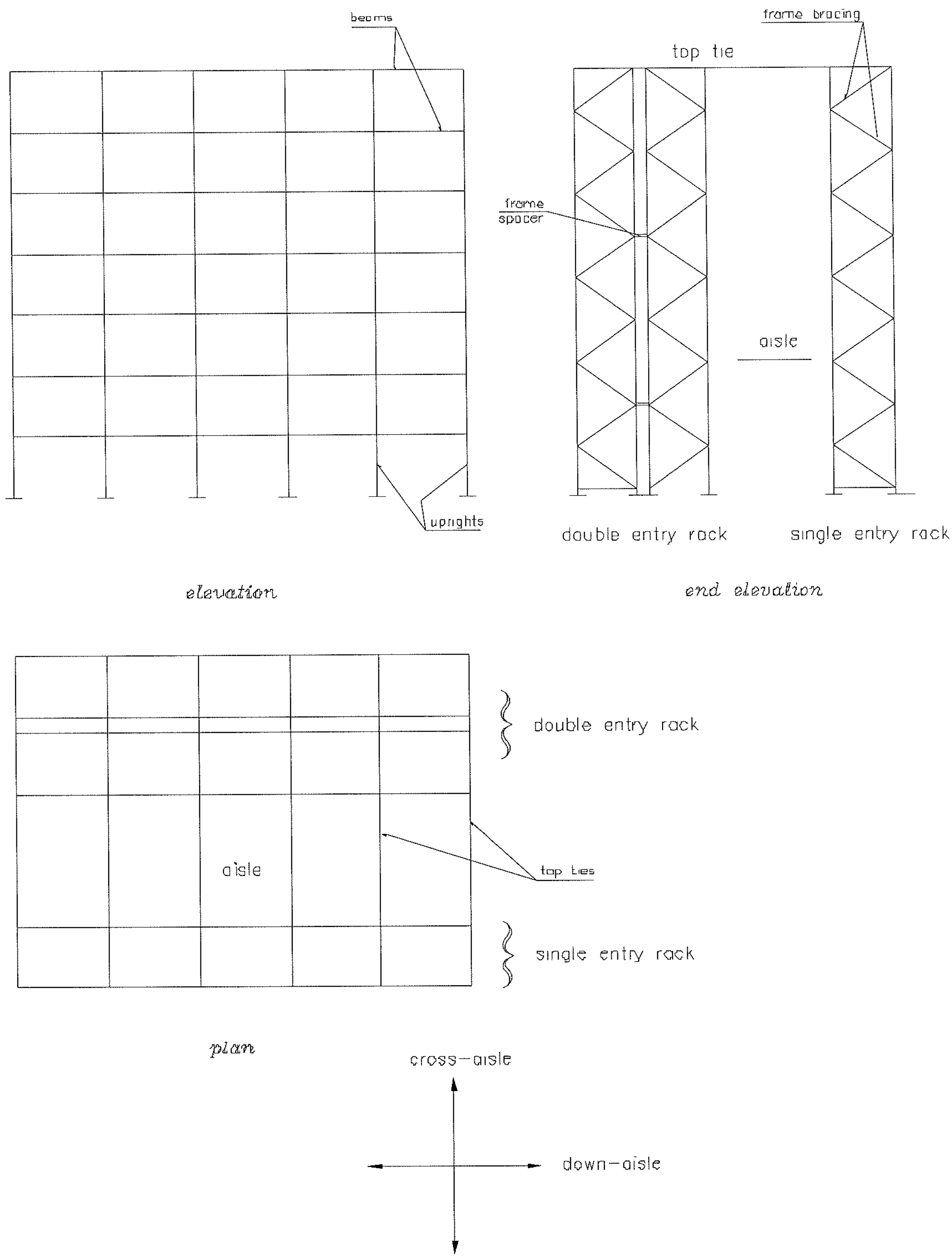


Fig. 1.13. Typical configuration of an unbraced pallet rack structure

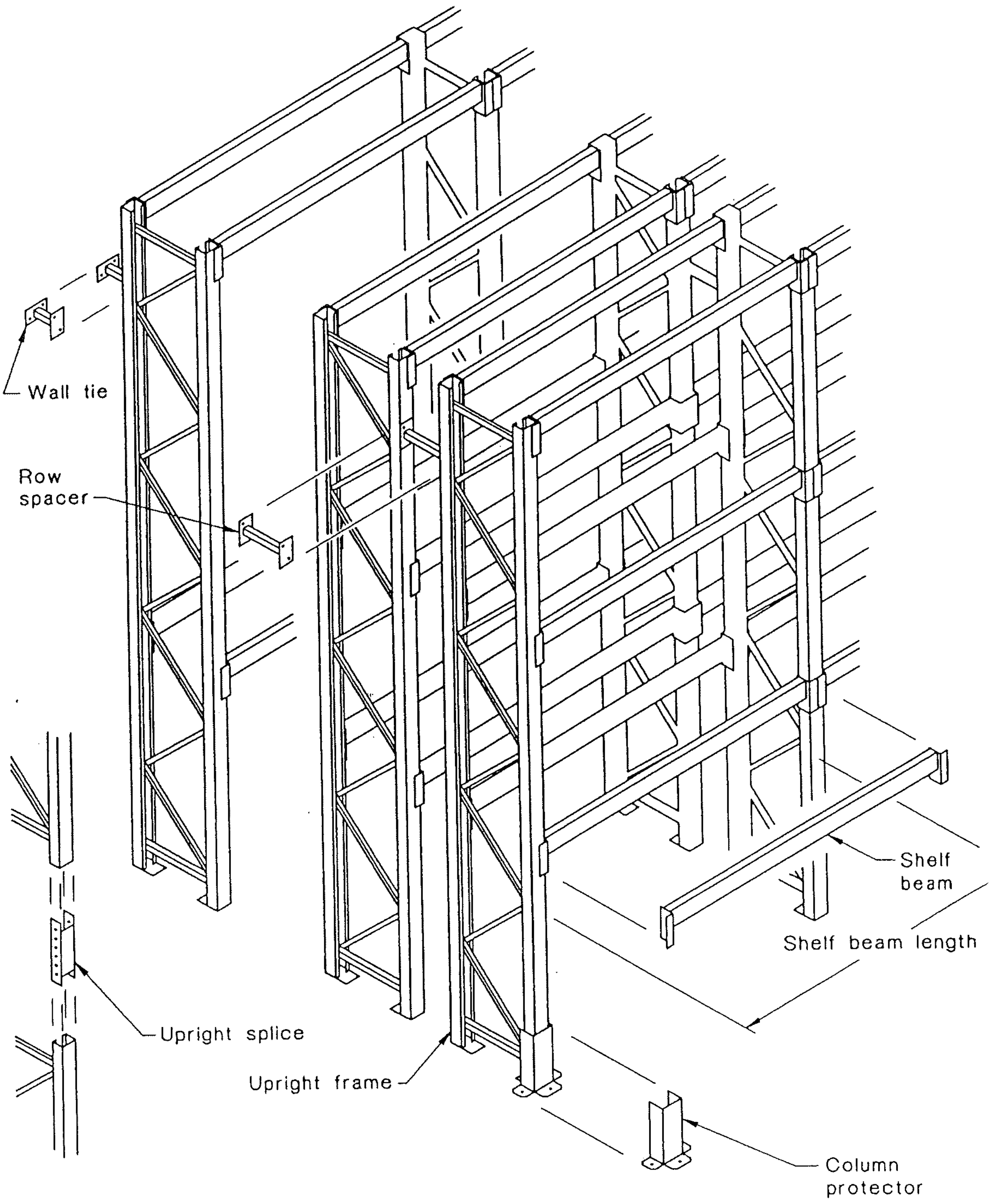


Fig. 1.14. Unbraced pallet rack

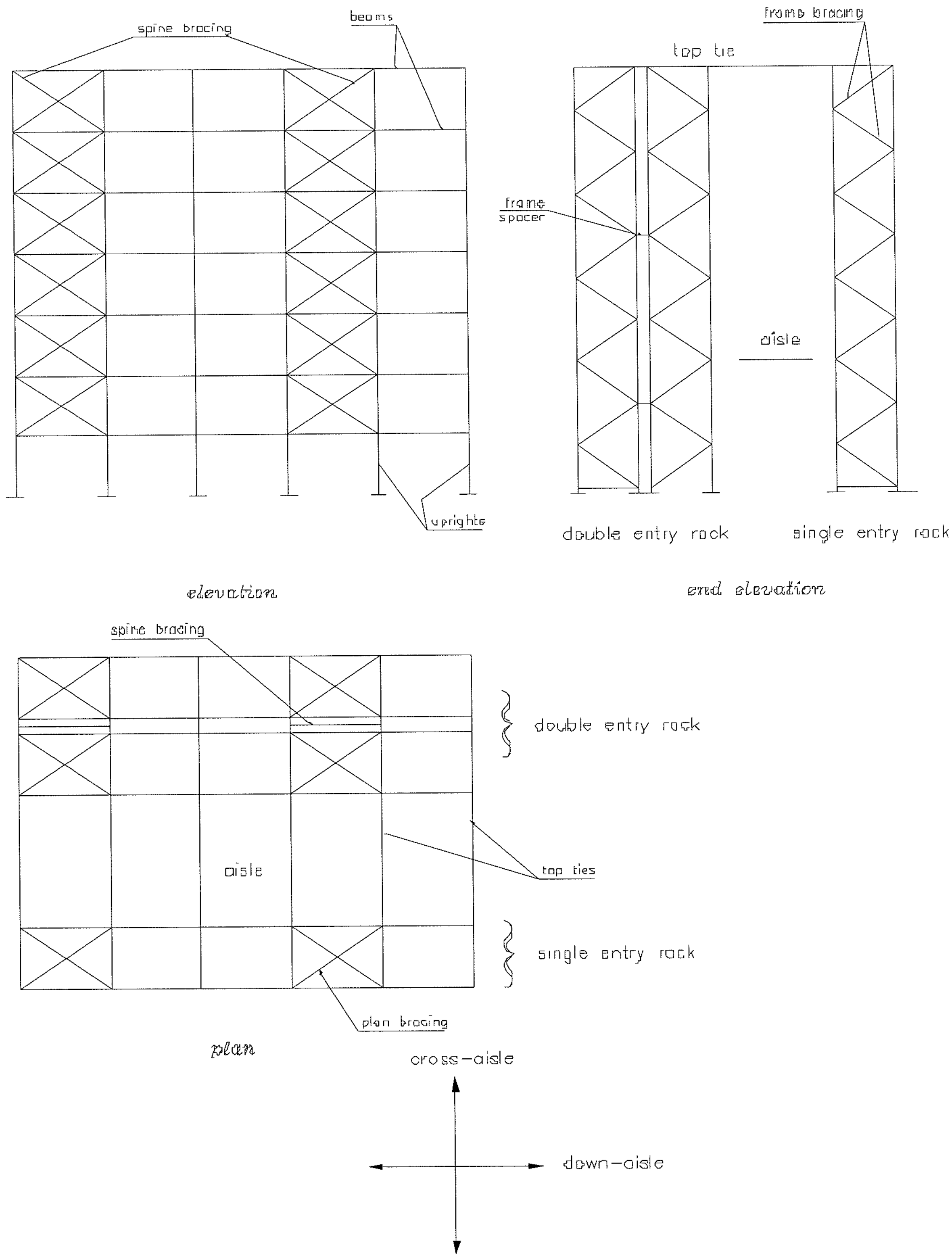
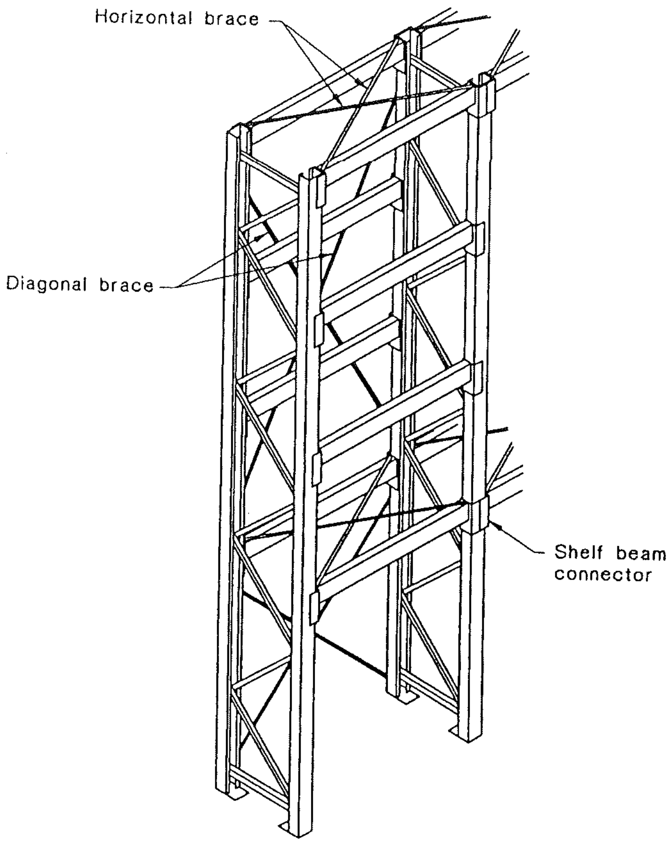
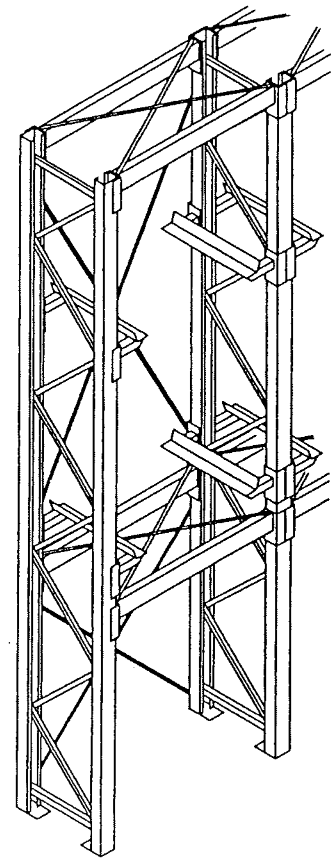


Fig. 1.15. Typical configuration of a braced pallet rack structure

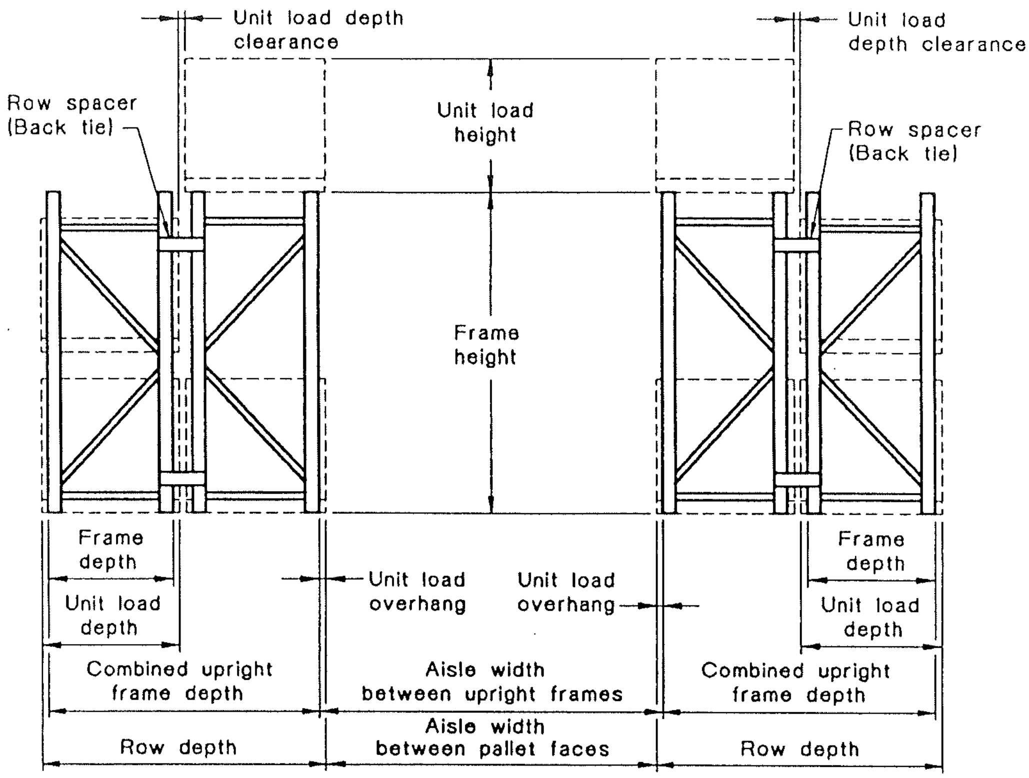


a-braced closed-face rack

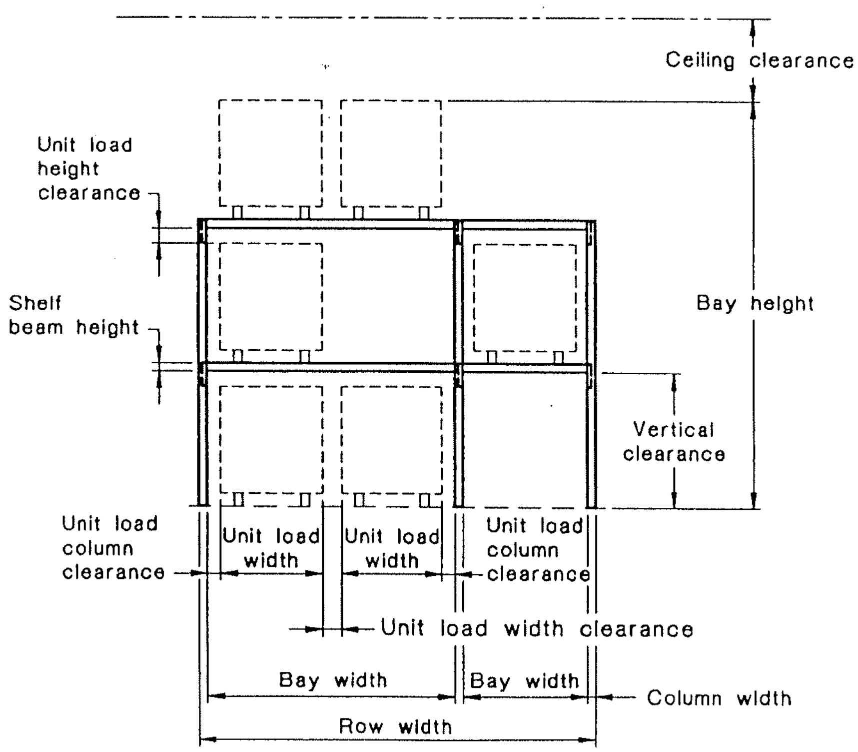


b-braced open-face rack

Fig. 1.16. Braced pallet rack



(a) Aisle width and related dimensions



(b) Clearance width and related dimensions

Fig. 1.17 Definitions

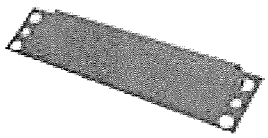


Fig. 1.18 Rowspacer

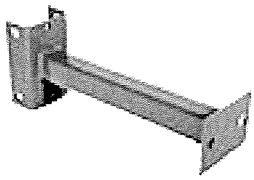


Fig. 1.19 Walltie

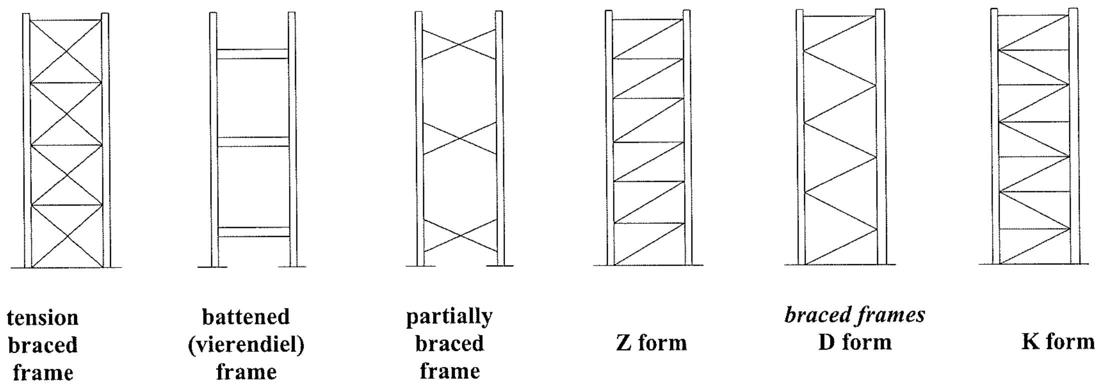
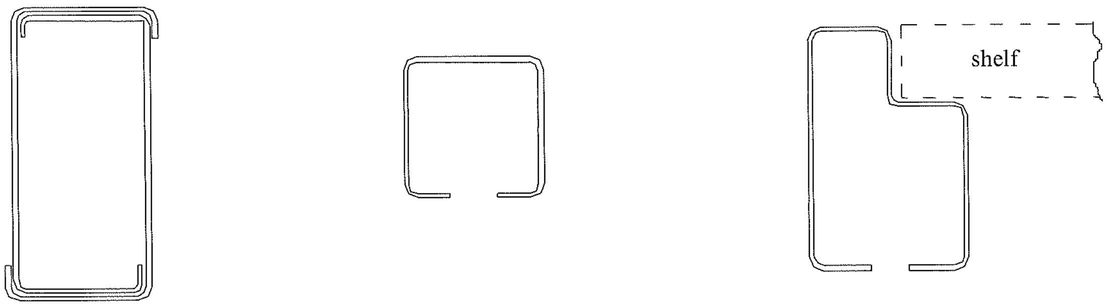


Fig. 1.20 Typical upright frames



a-box section *b-open section* *c-stepped open section*

Fig. 1.21. Typical beam profiles

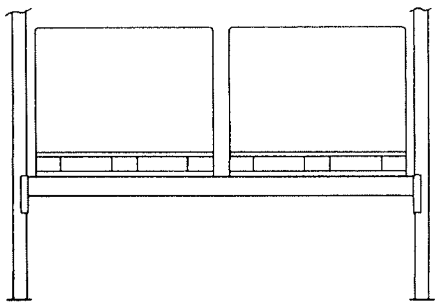


Fig. 1.22. Two pallet beam loading

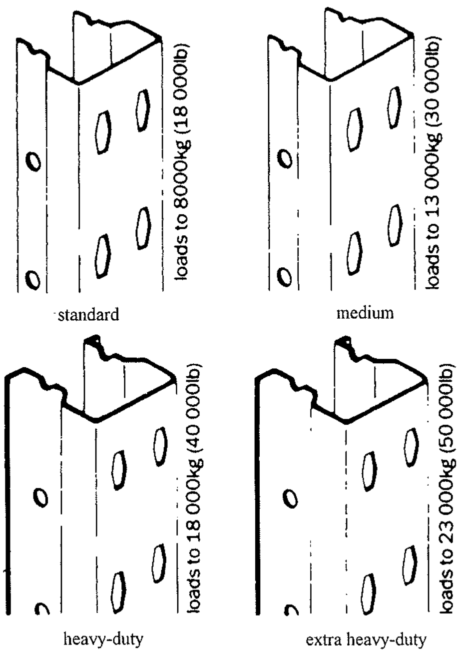


Fig. 1.23 Typical upright profiles

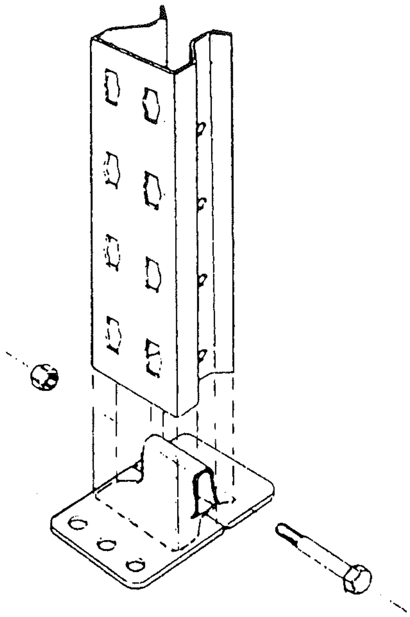


Fig. 1.24 Typical pallet rack baseplate

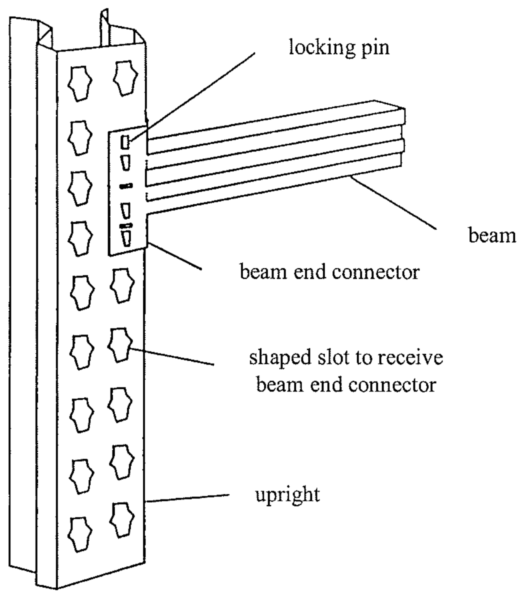


Fig. 1.25. Typical beam end connector

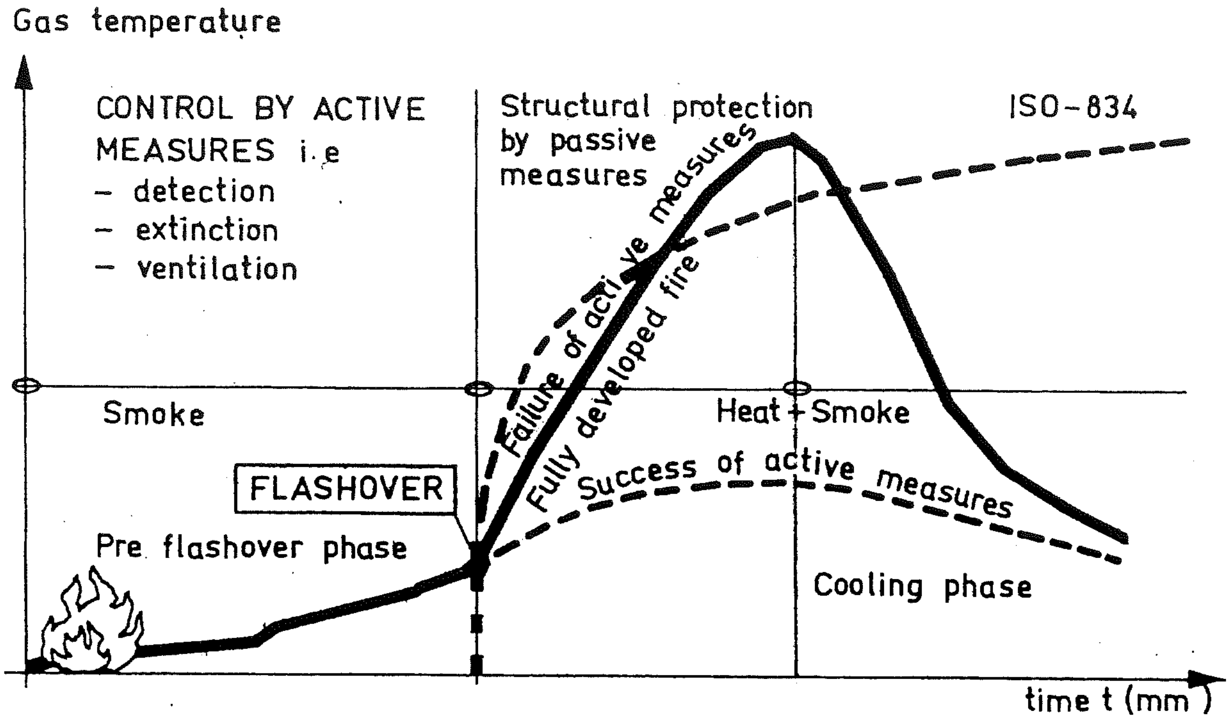


Fig. 1.26. Fire development

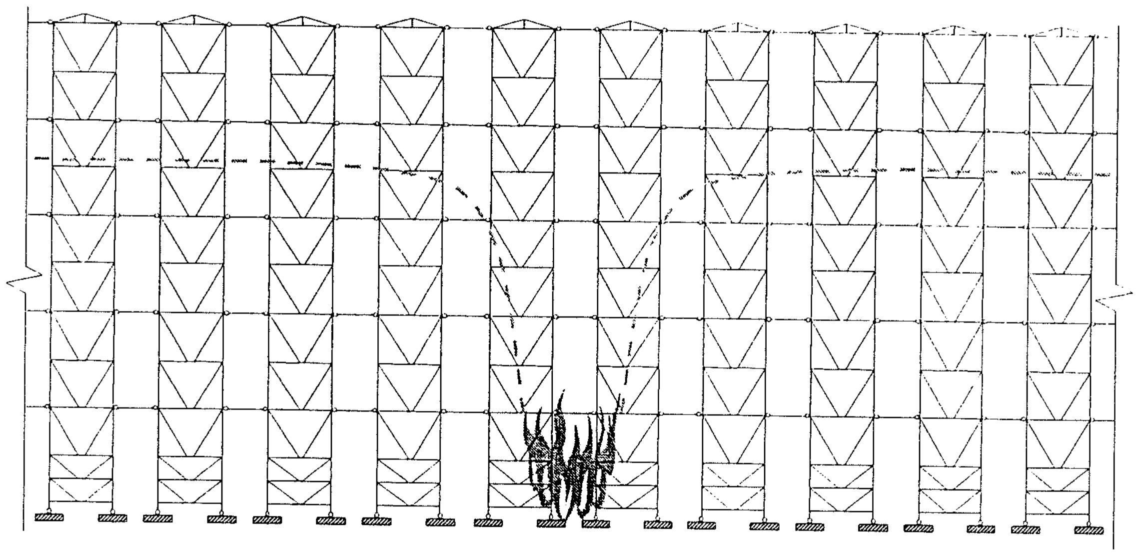


Fig. 1.27. Fire scenario

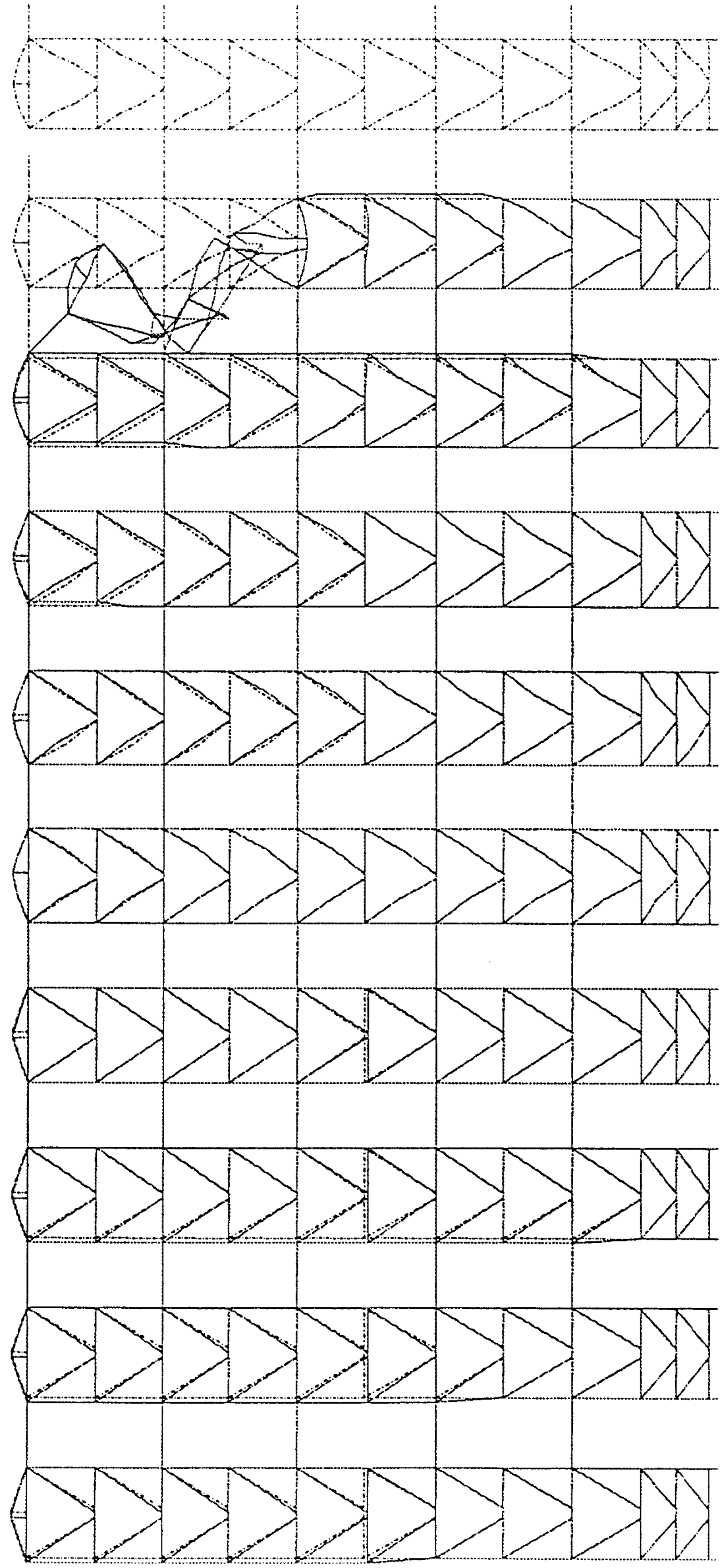


Fig. 1.28. Local collapse of second rack after 25 minutes

2. NUMERICAL FINITE ELEMENT MODELLING OF RESISTANCE AND STABILITY BEHAVIOUR OF PROCTER AND GAMBLE RACK STRUCTURE UNDER STATIC LOADING AT AMBIENT TEMPERATURE

2.1 Description of Procter and Gamble rack structure

The Procter and Gamble storage rack supported building considered for this study is made of 37 racks, supporting the pallets and the roof and has the following dimensions:

Width = 56 m
Length =156m
Height = 30m

The structure is of TRAVHYDRO type [TRA] and was designed by the GREISCH design office [GRE99].

Figure 2.1 presents the vertical longitudinal and the horizontal views of the structure. Figure 2.2 shows the transversal view. One rack has 10 levels with a vertical pitch of 2.75m and 18 bays for pallet storage. Each bay, from both sides, can support six pallets of 10kN (Fig. 2.3).

As shown in Figure 2.4, there are only 2 uprights supporting the pallets, the internal C200x60x15x3 beams being connected to the traverse C120x40x10x3. The external beams which are in the same time rails for the automatic pallet transport system, are G25x90x170x80x40x5 profiles, connected to the uprights by 4 M12 bolts at each connection.

The uprights are special hollow sections (Fig. 2.5), with holes near the rail connections, in order to realize the bolted joint (Fig. 2.6). The rails and the internal beams are continuous over each three bays; the end connections are realized with slotted holes for levels 1 and 2, as shown in Figure 2.7.

The vertical bracing system on the down aisle direction, shown in Figure 2.2, is placed between axes 5-8 and 14-17. The diagonals are rectangular 60x60x4 hollow sections for levels 1 to 3, and 60x60x3 respectively for levels 4 to 10 . The horizontal members of this bracing system are U60x50x4 sections.

The horizontal bracing system, of 38x2.5 circular sections is placed between axes 5-8 and 14-17, and it is shown in Figure 2.8.

The uprights floor connection is presented in Figure 2.9.

Figures 2.10-2.13 shows photos of the Procter & Gamble rack storage building during erection [TRA].

The uprights are made of stell S390 with the yield limit f_y = 390N/mm^2. All other elements are of steel S355 with f_y = 355N/mm^2.

2.2 3-D FEM model

2.2.1 Model description

As mentioned previously, in the down-aisle direction the rails are continuous over each 3 bays. Further, it will be demonstrated that the connections between rails and uprights have low rotational rigidity. Consequently, the pair of vertical bracings are, practically, the only elements able to provide horizontal stability to the down-aisle direction. For this reason, in the numerical study, a substructure representing three bays of the rack structure, which are corresponding to the vertical bracing system on the down-aisle direction was taken into account. The 3-D model is shown in Figure 2.14.

For the mechanical analysis at elevated temperature, this model is too complex to be introduced in the SAFIR program. Consequently, in order to simplify this analysis, equivalent 2-D models for cross and down - aisle directions have to be used. However, the 3-D model is necessary to calibrate these equivalent models, by means of static numerical analysis using AXIS-3D computer program.

Details of the 3-D model are shown in Figure 2.15a-d. The connection eccentricities, between rails and uprights, as well as between traverses and uprights, were taken into account. The vertical bracings, on both down and cross - aisle, and the horizontal ones have single bolt joints, so they are modeled as truss elements. The U60x50x4 elements of the vertical down - aisle bracings are modeled as beam type finite elements, with pinned connections on the lateral traverses, and rigid connected over the intermediate ones. In the same way, the C200x60x15x3 beams are continuously rigid connected on the intermediate traverses, and pinned on the lateral ones. Indeed, it is not necessary to develop a particular analysis on the real behavior of C beam - to - traverse connections, realized with LI 70x50x6 link elements, because, taking into account the low rigidity of connection elements, as well as the low torsional rigidity of the traverse, they behaves as pinned supports. The same remark is available for the connections of the U elements of the vertical down - aisle bracing system.

However, the rigidity of the bolted connections between the continuous G25x90x170x80x5 rails and the uprights is important to be evaluated and introduced in the FEM model. If pinned connections between the continuous rails and the uprights are considered, due to the fact that the base uprights supports are pinned too, the structure without vertical down - aisle bracings is a mechanism. The European recommendations for the design of static pallet racking systems [FEM98] provides no information about the computation of the rigidity of base uprights supports; there are only some recommendations about the tests on floor connections in order to evaluate their rigidity. When tests are not available, the floor connections must be considered as pinned. On the contrary, for the moment-resistant bolted connections between rails and uprights, different studies are available, in order to evaluate the rotational rigidity. Bryan [BRY92] gives a formula for the flexibility of a single bolt lap joint in shear, in terms of sheet thickness and considering the threaded or plain shank of the bolt in the connection. Using this formula, the rotational rigidity for different bolt arrangements can be determined. Zaharia [ZAH00a-b] developed similar studies on single bolt lap joints in shear, and improved the Bryan formula, introducing the diameter of the bolt as supplementary parameter. This formula is available for the bolt hole clearance of 1mm, considering the threaded portion of the bolt in connection. With this formula, the rotational rigidity of bolted connections can be evaluated. The computation formula for the rotational rigidity of the 4 bolts connection, between upright and rail, is presented in the following paragraph.

2.2.2 Rotational rigidity of bolted connections

2.2.2.1 Down-aisle connections

In the previous paragraph pinned or rigid behavior was considered for the connections of the vertical down-aisle bracing system, as well as for the connections of the C beams.

In order to evaluate the real behavior of the upright-to-rail 4 bolt connection, the formula proposed by Zaharia [ZAH00a-b] can be used to evaluate the rotational rigidity

$$K = \frac{6.8 a^2 \sqrt{d}}{\left(\frac{5}{t_1} + \frac{5}{t_2} - 1\right)} \frac{1}{\gamma_R} \quad \text{[kNmm/rad]} \qquad (2.1)$$

in which

- a = 136mm is the distance between bolts;
- d=12mm is the nominal diameter of the bolt;
- $t_{1,2}$ are the thickness of rail and uprights sections;
- γ_R =1.25 is the partial safety factor for ambient temperature

For further mechanical analisys at elevated temperature, the partial safety factor will be taken γ_a =1.0 for accidental situations, according to ECCS [ECCS].

EUROCODE 3 [EUR93] states the limits between which a connection can be classified as pinned, semi-rigid or rigid, accounting for the rigidity of the beam. If the following condition is fulfilled, the connection is considered to be semi-rigid for the case of braced frames:

$$0.5\ EI / L < K < 8\ EI / L \qquad (2.2)$$

in which

- E is the Young modulus;
- I is the moment of inertia of the beam;
- L the length of the beam.

For the present case, considering the partial safety factor for ambient temperature, formula (2.1) gives a value of 313700kNmm/rad of the connection rigidity, while 50% of the beam rigidity is of 323300 kNmm/rad. It can be observed that, considering the EC3 classification criteria, the connection rigidity is, practically, on the upper limit of the range for pinned assumption. However, in the stability analysis of the structure, on the down-aisle direction, a comparison considering the real semi-rigid behavior of the connections and the pinned ones, it is interesting to made.

Considering the patial safety factor for fire design, the connection is semi-rigid according to the EC3 classification, so in the further analysis of the rack structure at elevated temperatures the rotational rigidity of the bolted rail - to - upright connection has to be taken into account.

2.2.2.2 Cross-aisle connections

As stated in the previous paragraph, the bracing connections are pinned.

In order to classify the behavior of traverse - to - upright connection, the following formula may be applied for the rotational rigidity [ZAH00a-b]:

$$K = \frac{3.4a^2\sqrt{d}}{\left(\frac{5}{t_1}+\frac{5}{t_2}-1\right)}\frac{1}{\gamma_R} \text{ [kNmm/rad]} \quad (2.3)$$

in which the parameters have been previously defined.

The value of the rotational rigidity of connection, computed with formula 3, represents less than 17% of the EC3 criteria, so the connection is assumed to be pinned.

2.2.3 Loads

The design loads at ambient temperature, given by the combination of permanent and storage loads, according to EUROCODE 1 [EUR95] and as considered in the GREISCH calculation notes [GRE99] are as following:

Permanent loads:	- 0.5kN/m2 at each level
	- 0.4 kN/m2 roof
Variable loads:	- 60 kN/bay at each level - pallets

The partial safety factors are γ_G = 1.35 for the permanent loads and γ_G = 1.5 for the variable load.

<u>2.3. Cross - aisle stability analysis</u>

The bracing in the plane of frames provides the cross-aisle stability, so the 2-D model on this direction is the cross-aisle frame itself. The bracings are pinned at the ends. The upright - traverse connections are also pinned, taking into account the joint rigidity and the EC3 classification, as it was stated in paragraph 2.2. The plane model for cross - aisle stability computation is given in Figure 2.15-a.

The eigen buckling analysis performed with AXIS-3D computer program gives the value of 4.35 for the critical load factor, for the combination of loads presented previously, with the corespondent eigen buckling mode shown in Figure 2.16.

2.4. Down – aisle stability analysis

2.4.1. Down - aisle equivalent plane model

In order to calibrate the equivalent 2-D computation model on the down - aisle direction, in which the vertical bracing system must be brought out in the same plane as the uprights, by means of some equivalent beam elements, the upright-rail connections will be considered as pinned. The two diagonals and the horizontal U element, without any other vertical members compose a single cell of the vertical bracing system.

The equivalent 2-D model is shown in Figure 2.17. The vertical bracing system is moved in plane of the uprights (see dotted points in Figure 2.17) and connected to the uprights by a beam element, which is able to simulate the horizontal and vertical flexibility of bracing connections. The vertical flexibility is given by the assembly of traverse and vertical bracings of the cross-aisle frame. The horizontal flexibility is given by the horizontal bracing system, which is provided for all levels, on the middle – bay.

The vertical flexibility of the bracing connections is simulated by the axial rigidity of the equivalent element, computed by the following formula :

$$A_{equ} = K_{vert} L / E \qquad (2.4)$$

in which

- L - length of the equivalent element;
- E - the Young modulus;
- K_{vert} - rigidity of the assembly of traverse and vertical cross-aisle bracing.

The numerical 2-D model from which K_{vert} can be computed is shown in Figure 2.18.

The horizontal flexibility of the bracing connections is simulated by the lateral displacement rigidity of the equivalent element. The moment of inertia of the equivalent beam element is computed by the following formula :

$$I_{equ} = K_{oriz} L^3 / 3E \qquad (2.5)$$

in which

- L - length of the equivalent element;
- E - the Young modulus;
- K_{oriz} - the lateral displacement rigidity of the horizontal bracing system.

The numerical plane model from which K_{oriz} is be computed is given in Figure 2.19.

Table 2.1 gives a comparison between the horizontal displacements computed with the 3-D model and the 2-D equivalent one, using a horizontal load of 10kN applied at each rail level. In the equivalent 2-D model, the diagonals and U horizontal elements of the bracing system were considered with half of their cross section characteristics.

Table 2.1. Horizontal displacement [mm] - comparison between 3-D model and 2-D equivalent one

Level	3D Model (1)	Equivalent Model (2)	$\frac{(2)}{(1)}$
2	6.12	6	0.981
3	14.52	14.4	0.992
4	22.22	22	0.990
5	29.53	28.7	0.972
6	44.44	43.2	0.972
7	59.19	57.3	0.968
8	72.08	69.7	0.967
9	83.22	80.4	0.966
10	91.67	89.2	0.973

It can be observed only small differences, less than 3.6%, between the results obtained with the two models. Therefore, for further analysis of the down-aisle direction, the equivalent 2-D model can be considered.

2.4.2. Stability analysis

The eigen buckling analysis, performed with AXIS-3D computer program, for the equivalent down-aisle 2-D model, considering the upright - rail connections as pinned, gives the value of 2.84 for the critical load factor, for the load combination presented in paragraph 2.2.3. The corespondent eigen buckling mode is shown in Figure 2.20.

In order to emphasize the importance of the flexibility of the bracing connections, the results from the equivalent 2-D model is compared with the simplified case of the bracing system brought out in the plane of the down-aisle frame and connected directly to the uprights, without any suplemmentary equivalent beam elements. Table 2.2 gives the comparison between the horizontal displacements, considering the same case of horizontal load as mentioned in paragraph 2.4.1, and the comparison between the critical load factors.

It can be observed that, considering the simplified model with the bracing system connected directly to the uprights, the critical load factor is increased with 5.6% only, while the horizontal displacements are reduced with more than 36% in this case. Taking into account that the critical load factor is less than 10, according to EC3 a second order analysis is to be performed for the design of the structure, and consequently the structural sensitivity to lateral displacements is very important in this case.

Furthermore, in the further mechanical analysis at elevated temperatures, the Young modulus is decreasing with the temperature, and accentuates this sensitivity. Thus, even if the simplified model represents an easiest approach for design, the equivalent model considering the vertical and horizontal flexibility of the assembly which conects the bracing system to the down-aisle frame must be considered.

Table 2.2 Horizontal displacement [mm] and critical load factor - comparison between equivalent and simplified model

	Equivalent model (1)		Simplified model (2)		(2)/(1)	
Level	D [mm]	α_{cr}	D [mm]	α_{cr}	D	α_{cr}
2	6	2.63	5.1	2.79	0.850	1.056
3	14.4		10.1		0.701	
4	22		14.5		0.659	
5	28.7		18.1		0.631	
6	43.2		28.6		0.662	
7	57.3		39.1		0.682	
8	69.7		48.8		0.700	
9	80.4		57.5		0.715	
10	89.2		65.5		0.734	

Table 2.3 presents the comparison between the horizontal displacements and critical load factor for the equivalent 2-D model, considering pinned or semi-rigid upright - to - rail connections.

Table 3. Horizontal displacement [mm] and critical load factor - comparison between equivalent model for pinned and semi-rigid connections

	Pinned connections (1)		Semi-rigid connections (2)		(2)/(1)	
Level	D [mm]	α_{cr}	D [mm]	α_{cr}	D	α_{cr}
2	6	2.63	5.3	2.76	0.883	1.046
3	14.4		13.7		0.951	
4	22		21.4		0.972	
5	28.7		28.3		0.986	
6	43.2		42.2		0.977	
7	57.3		55.7		0.972	
8	69.7		67.8		0.973	
9	80.4		78.2		0.973	
10	89.2		87.1		0.976	

It can be observed that there are no important differences between the two cases; as shown in paragraph 2.2, the rigidity of the upright - to - rail connection is at the border of the pinned range for this case.

As shown in paragraph 2.2.1, considering the value of the rotational rigidity of the upright - to - rail connection for fire design, with the partial safety factor γ_a =1.0 for accidental situations, the connection is clasified as semi-rigid. Table 2.4 gives the comparison between the horizontal displacements and critical load factors, considering in the rotational rigidity formula (2.1) the partial safety factor as 1.25, for design at ambient temperature, or as 1.00, for fire design.

Table 2.4. Horizontal displacement [mm] and critical load factor - comparison between equivalent model with rotational rigidity for ambient and elevated temperature

Level	Ambient temperature $\gamma_R = 1.25$ (1)		Elevated temperature $\gamma_R = 1.00$ (2)		$\frac{(2)}{(1)}$	
	D [mm]	α_{cr}	D [mm]	α_{cr}	D	α_{cr}
2	5.3		5.3		1.000	
3	13.7		13.7		1.000	
4	21.4		21.3		0.995	
5	28.3		28.1		0.993	
6	42.2	2.76	42.1	2.78	0.997	1.007
7	55.7		55.6		0.998	
8	67.8		67.7		0.998	
9	78.2		78		0.997	
10	87.1		86.9		0.998	

It can be observed that practically there are no differencies between the two cases. Even if the design rotational rigidity of the upright - to - rail connection is 25% greater for the analysis at elevated temperatures, the rigidity is still low, representing 0.6 from the beam rigidity (EI / L) while the limit for rigid assumption is 8 times the beam rigidity, as shown in formula (2.2). Furthermore, for the substructure of three bays considered in this analysis, only the connections of the interior uprights are semi-rigid, those of the lateral ones being pinned. That means that such a low increase in the rotational rigidity is not supose to have an important effect at structural level.

Consequently, in order to simplify the numerical model for the mechanical analysis at elevated temperatures, the upright - to - rail connections can be assumed as pinned. It can be observed that, in this case, for the down-aisle direction the other series of three bays on which the rails are continuous, not provided with vertical bracings, are mechanisms. So, practically, the entire down-aisle direction is stabilised only by the pair of two vertical bracing systems.

2.5. Conclusions of static and stability analysis

Equivalent 2-D models for both cross-aisle and down-aisle directions have been established for the static and stability analysis of the Procter & Gamble rack structure.

The cross-aisle 2-D model is the cross-aisle frame itself.

For the down –aisle direction, the problem is more complex, due to the fact that the vertical bracing system is not in the plane of uprights. The down – aisle 2-D model is built considering equivalent beam elements, in order to simulate their real effect into the 3-D structure.

The connections between rails and uprights are semi-rigid, very close to the pinned behavior in this case. For further mechanical analysis at elevated temperatures, the connections will be assumed as pinned.

The stability analysis at ambient temperature proved that the down-aisle direction is the weakest one, the critical load factor representing less than 60% of the critical load factor for the cross-aisle direction. However, for the thermal analysis using SAFIR program, both directions will be analyzed; different phenomena due to the fire action may affect and change the structural response.

For both directions the critical load factor resulting from the stability analysis at ambient temperature is less than 10 and consequently, according to EUROCODE 3, the structure is sensitive to second order effects. The sensitivity to lateral displacements is accentuated in a mechanical analysis at elevated temperatures, taking into account that the Young modulus is descreasing with the temperature. In this conditions, according to EUROCODE 3, a second order analysis must be performed for the mechanical analysis of the rack structure at elevated temperatures, for both directions, taking into account the global and local imperfections.

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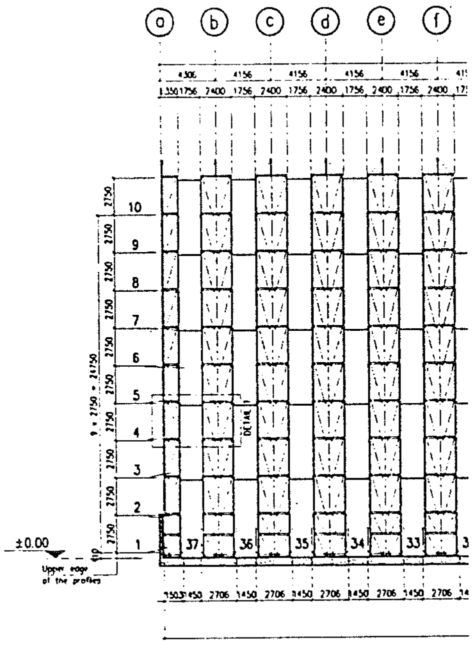
a
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9 × 2750 = 24750
DETAIL
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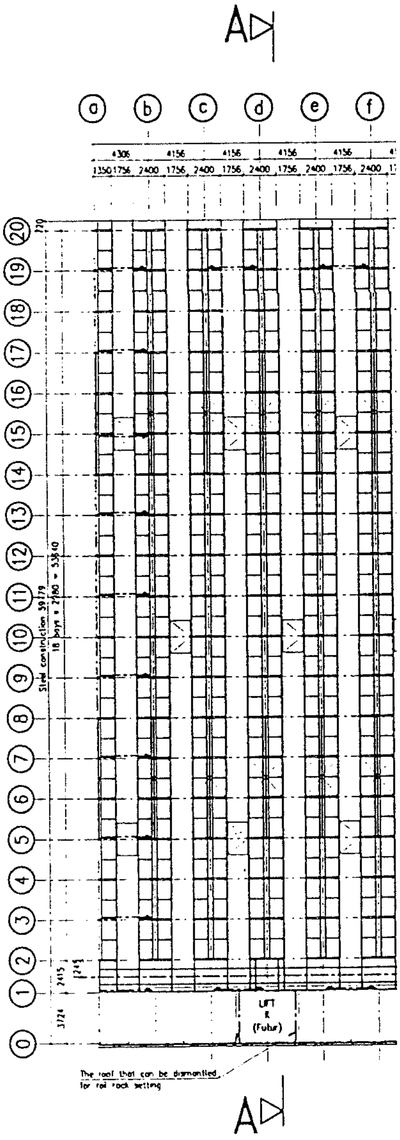
Upper edge of the profiles


A
a
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Steel construction 59179
18 bays × 2780 = 53840
LIFT
(Futur)
The roof that can be dismantled for rail rack setting
A

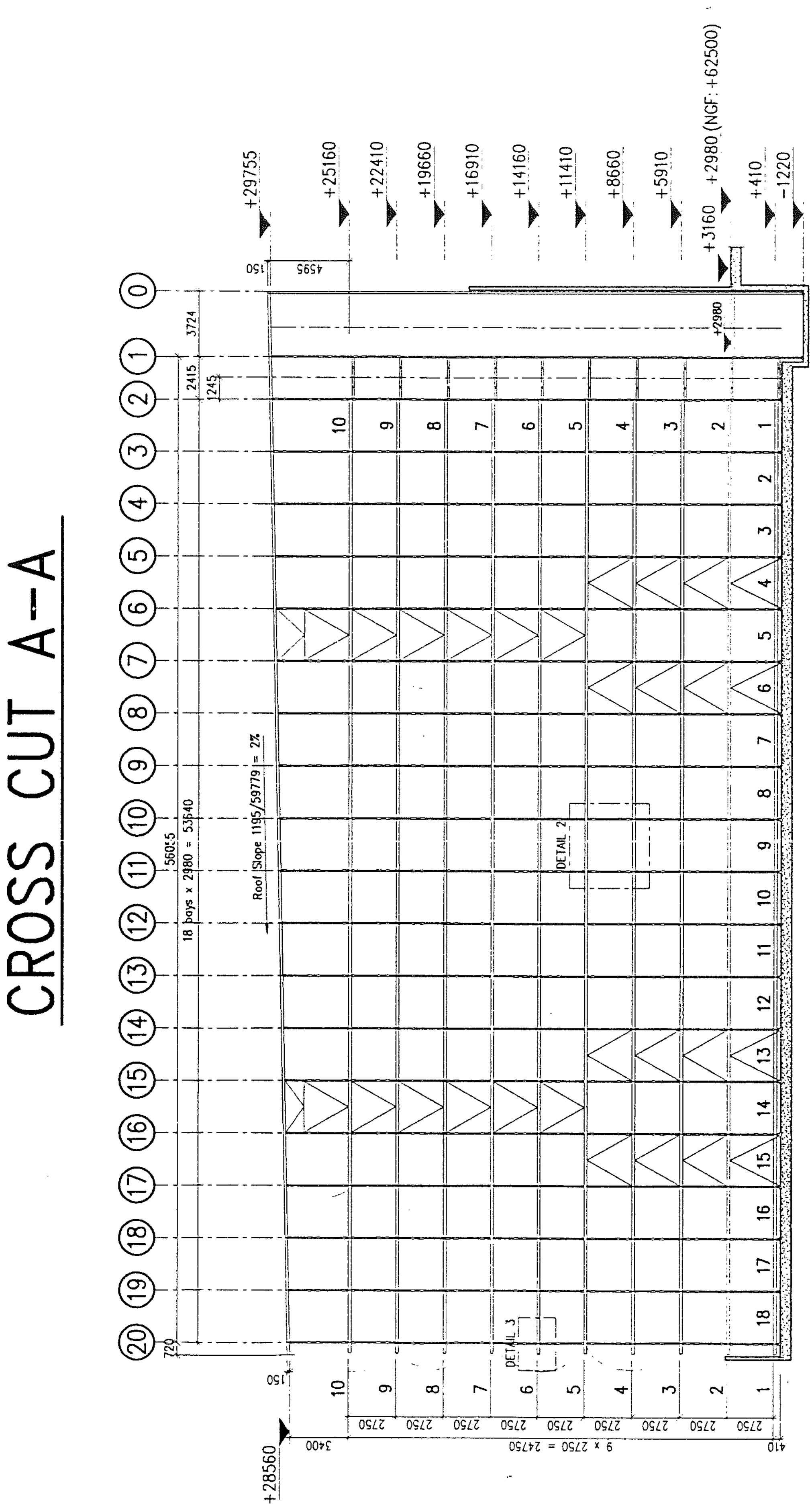

Fig. 2.2. Transversal view

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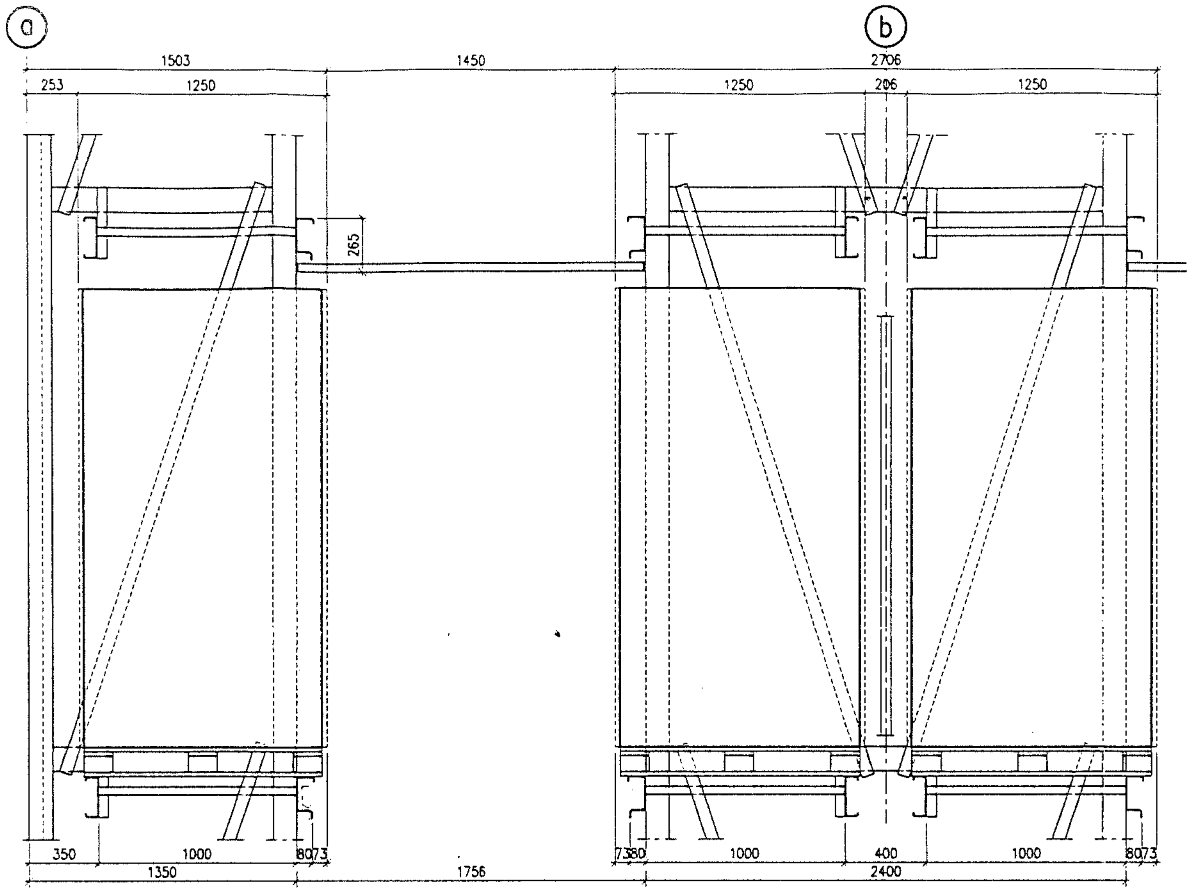

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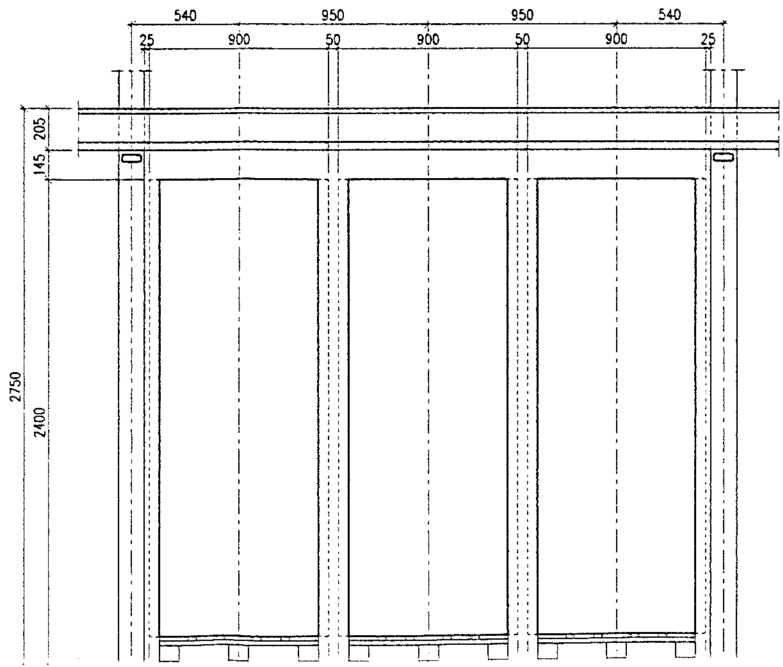


Fig. 2.3. Pallet disposal

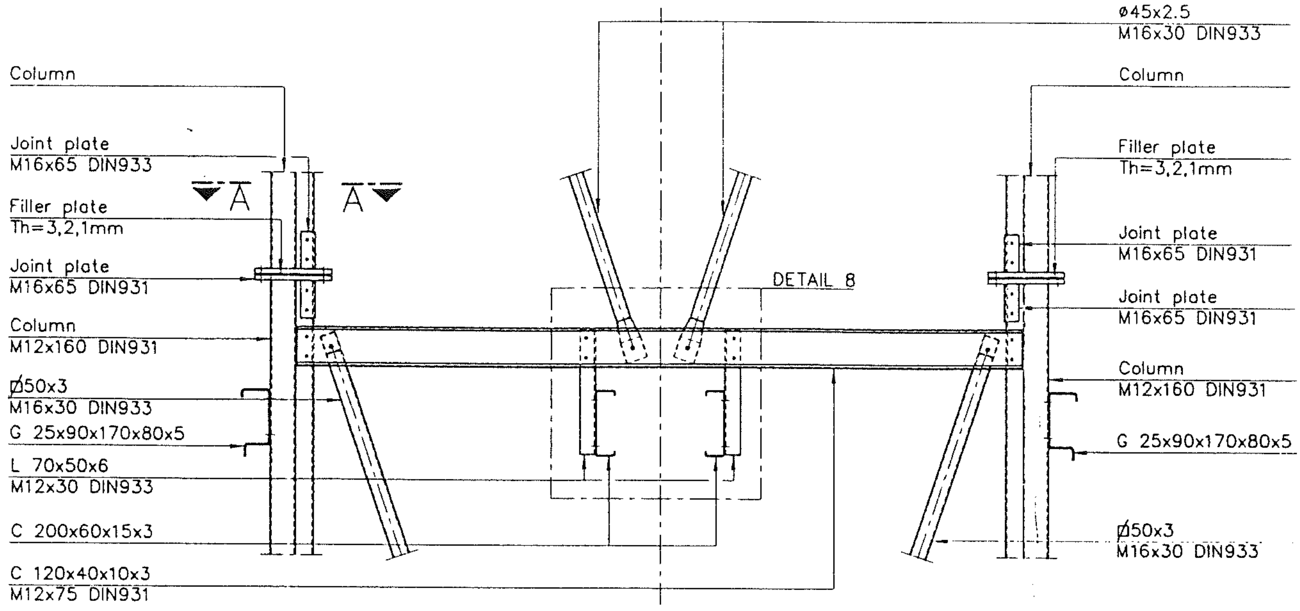


Fig. 2.4. Cross-aisle detail

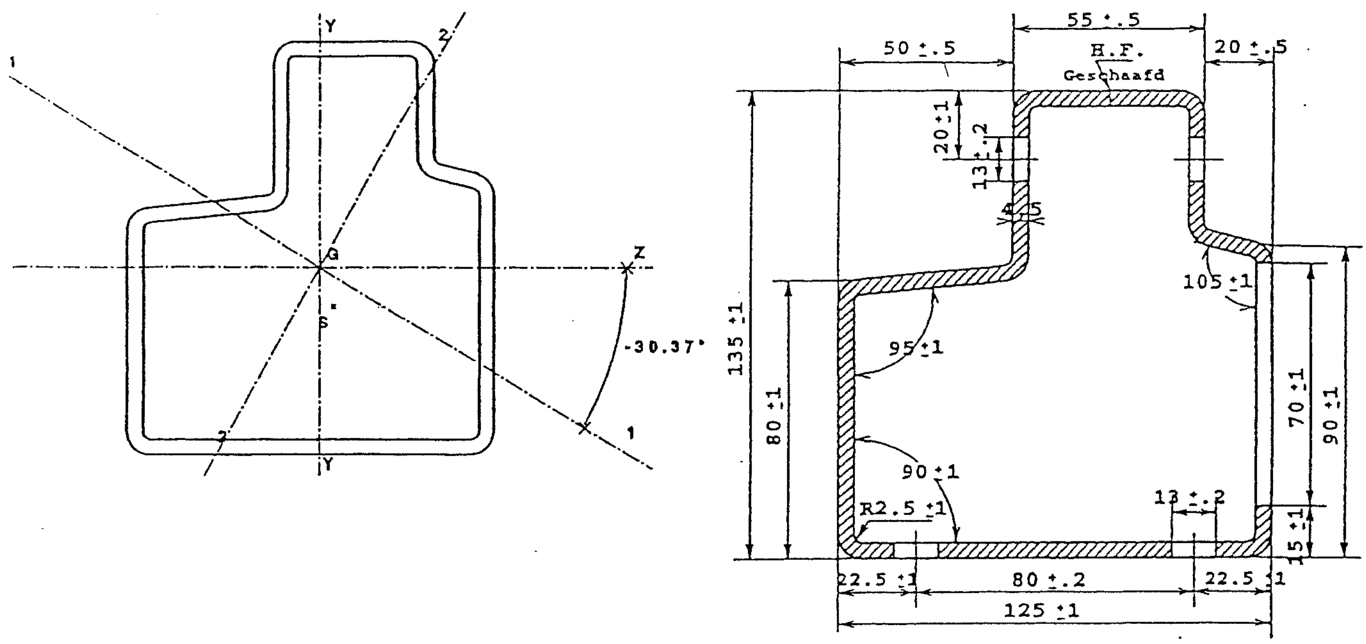


Fig. 2.5. Uprights cross-section

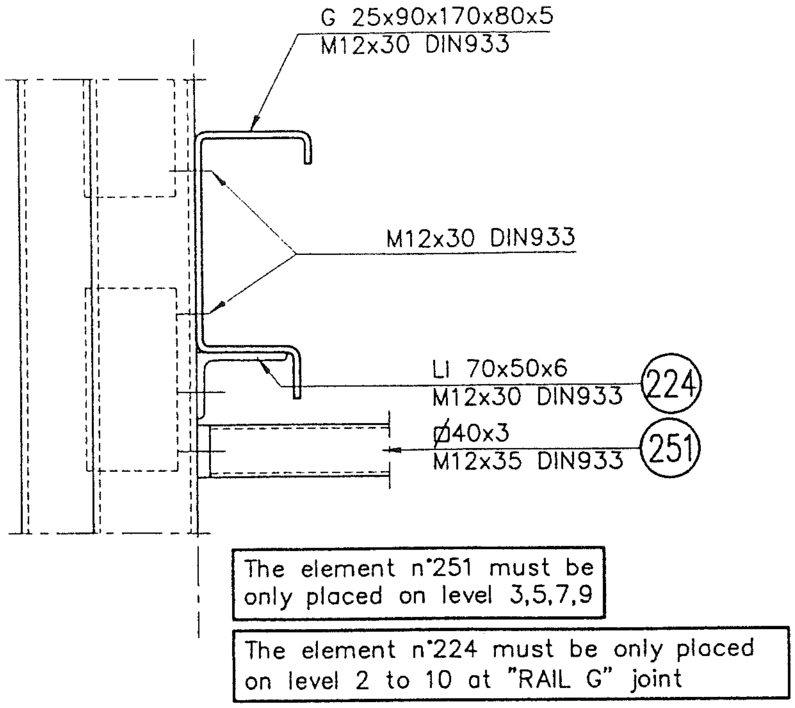


Fig. 2.6. Connection detail

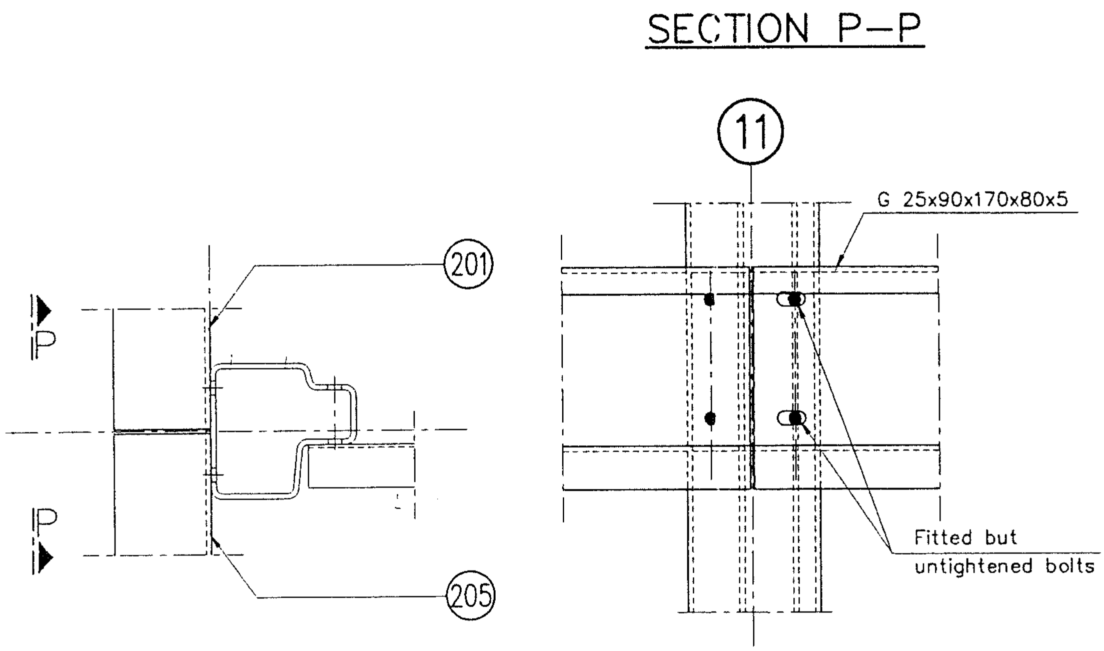


Fig. 2.7. End connection of the continuous rail

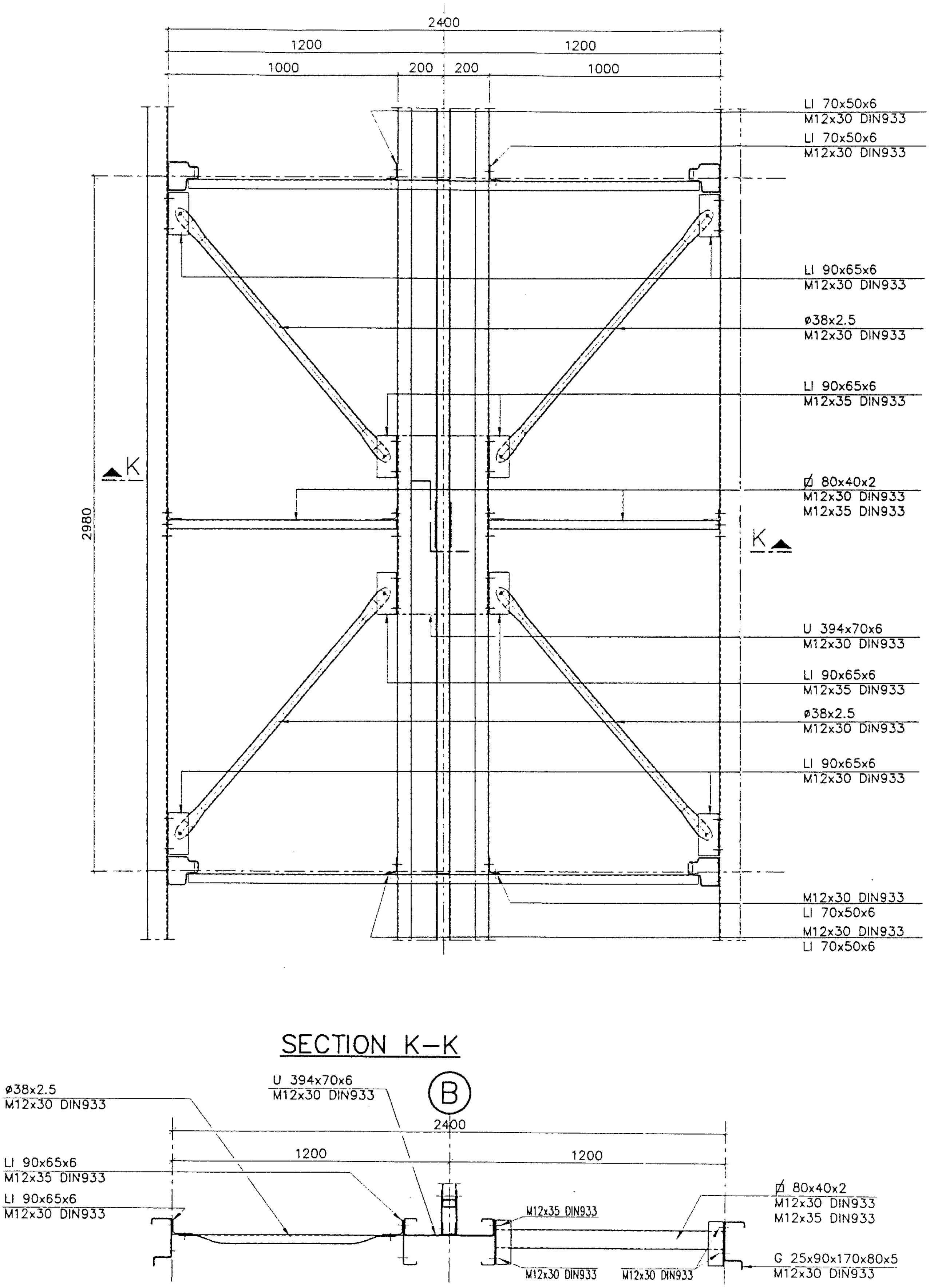


Fig. 2.8. Horizontal bracing system

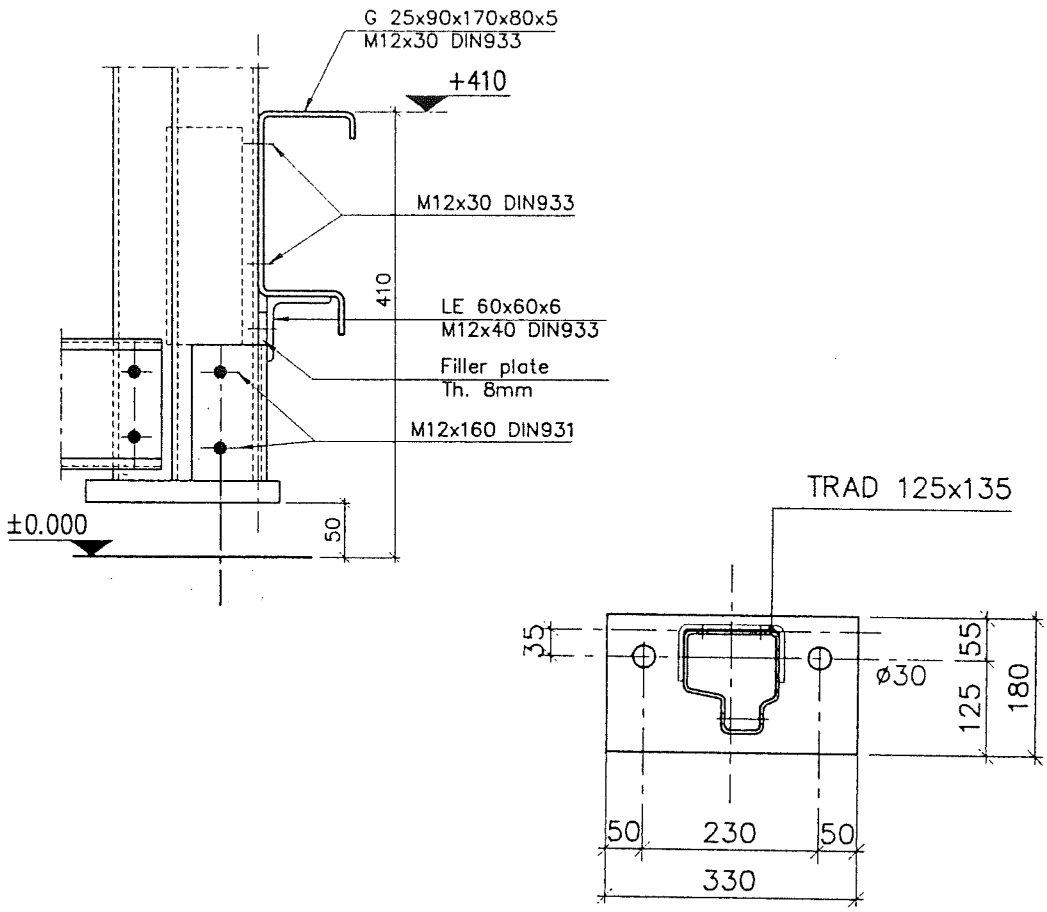


Fig. 2.9. Floor connections

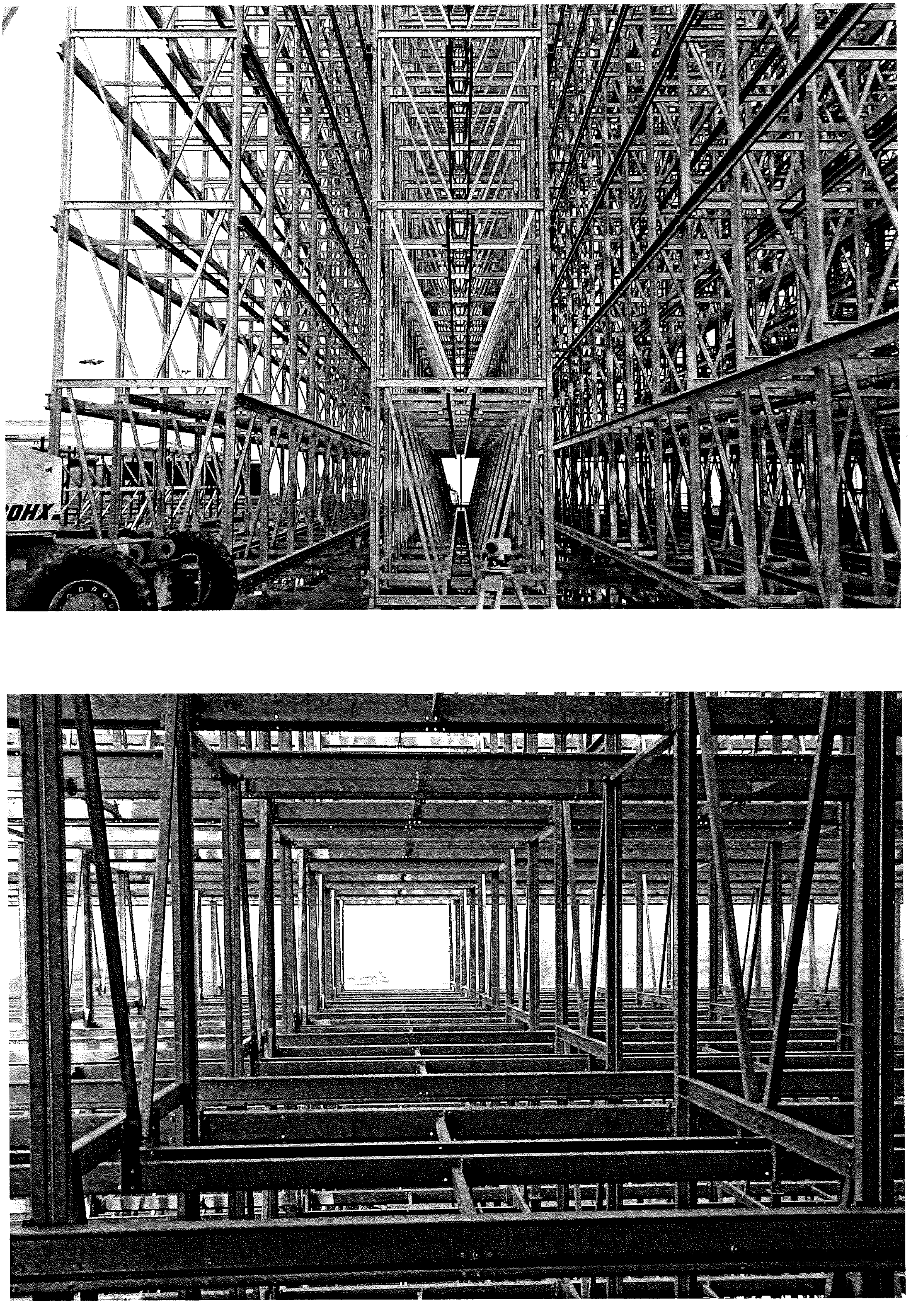


Fig. 2.10a. General views

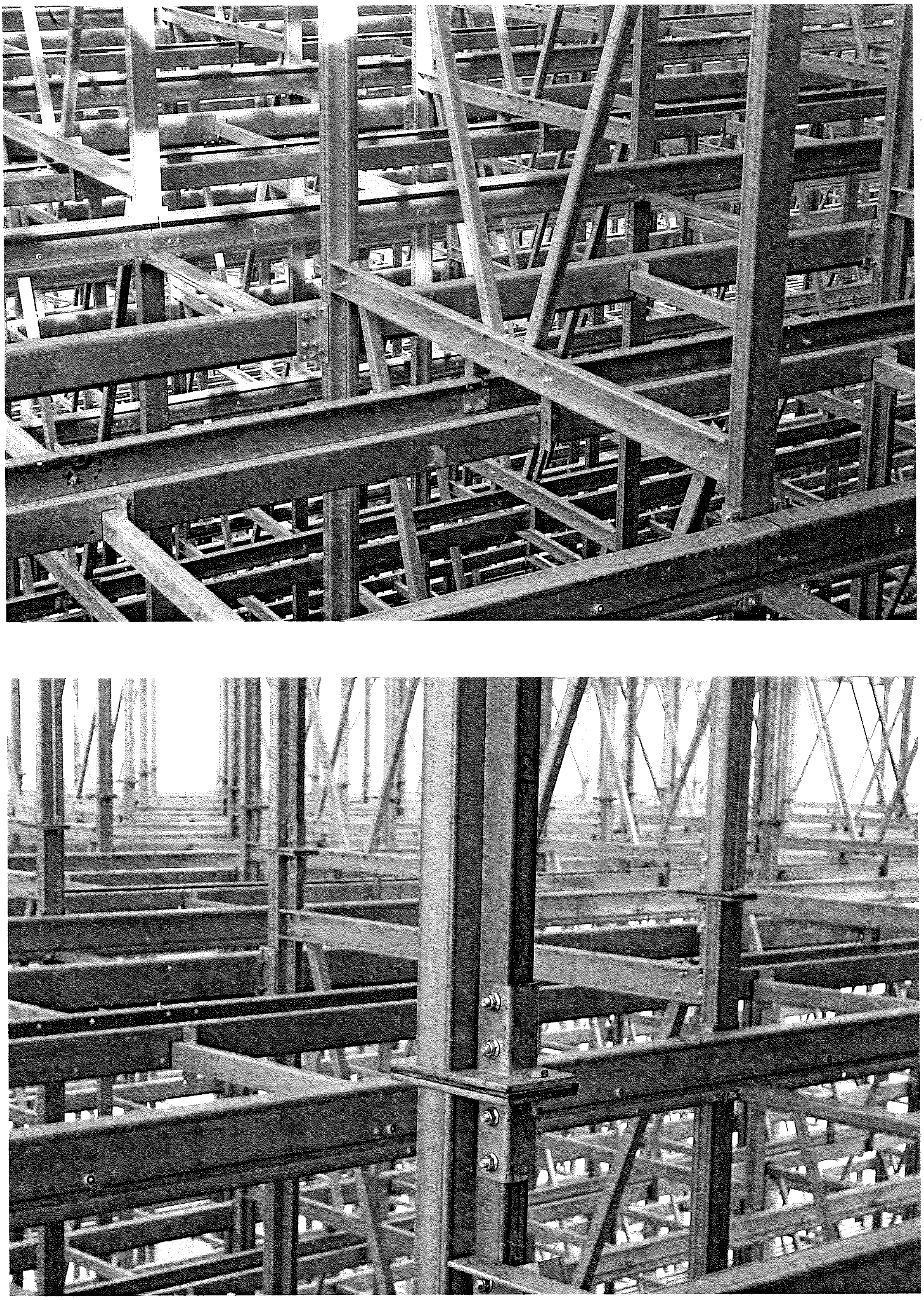
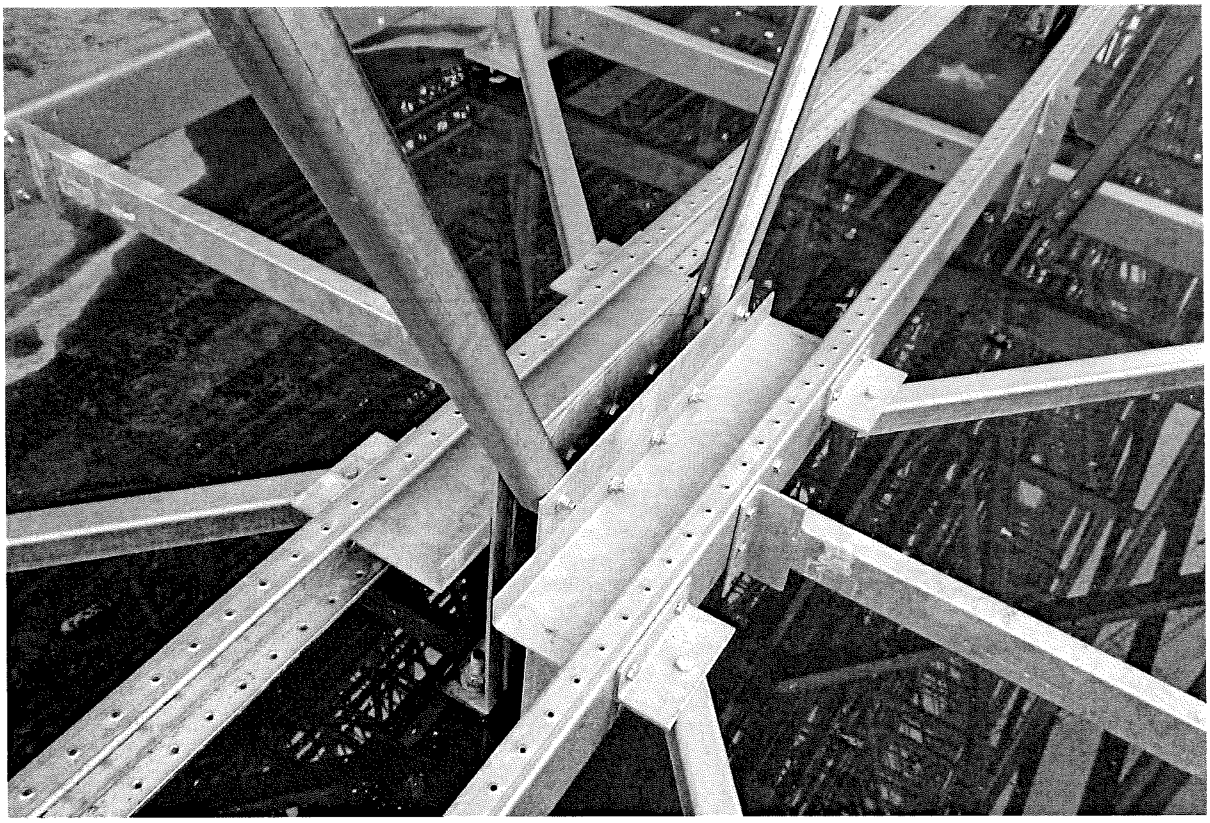


Fig. 2.10.b General views



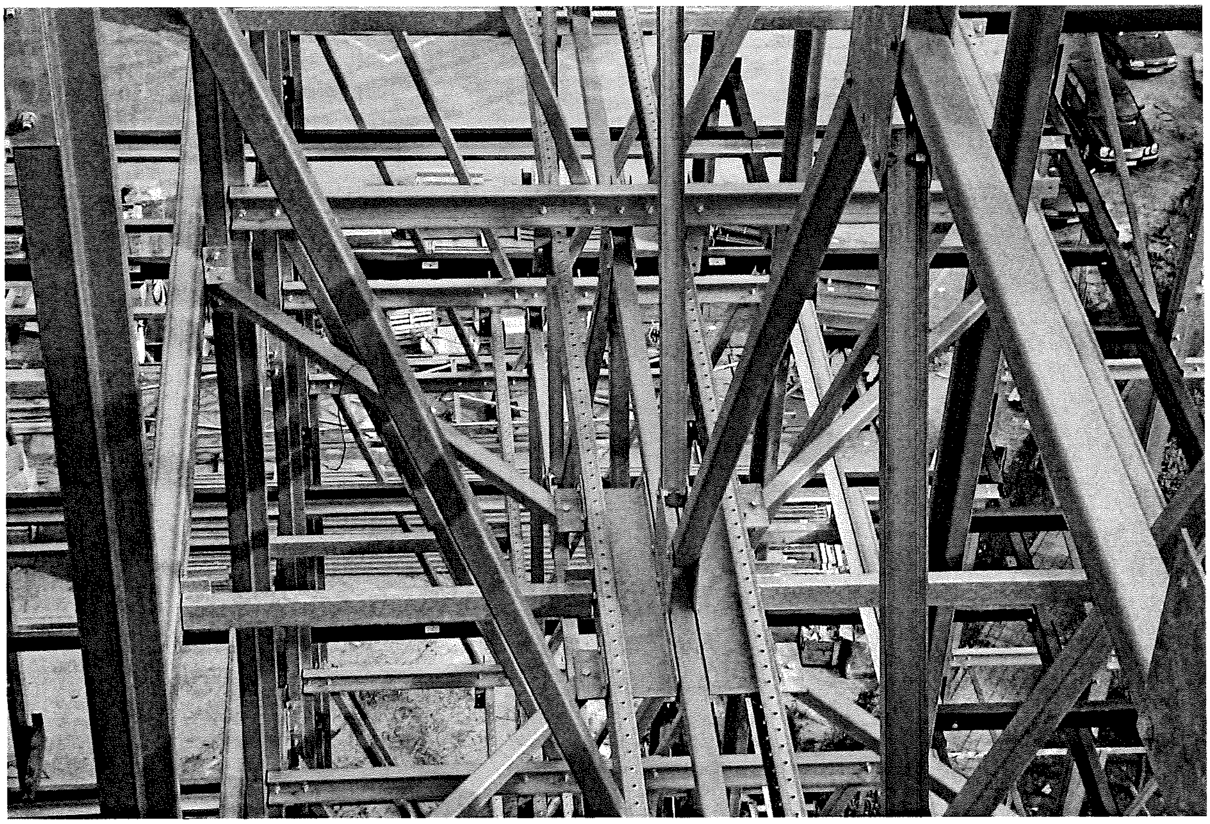


Fig. 2.11. Horizontal bracing system

Fig. 2.12. Down-aisle bracing system

Fig. 2.13. Roof structure

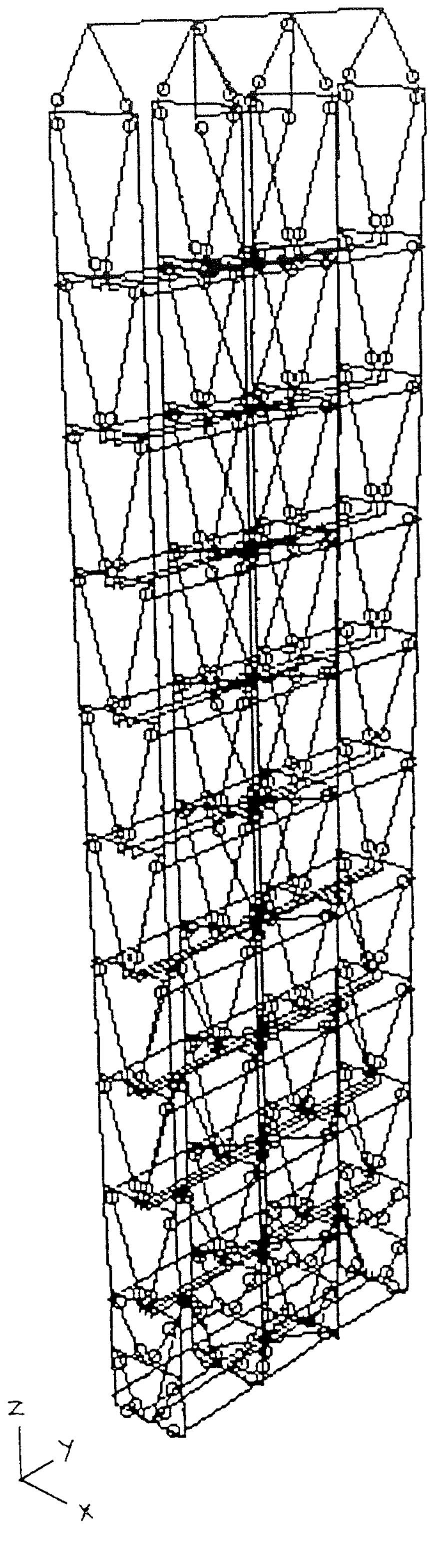


Fig. 2.14. 3-D numerical model

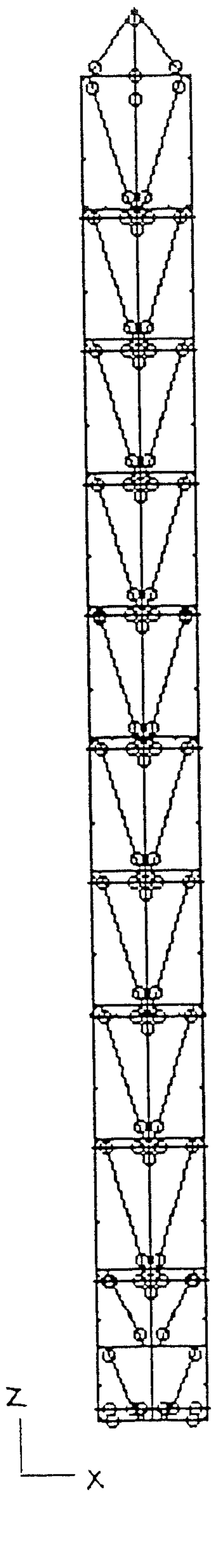


Fig. 2.15-a. Cross-aisle direction

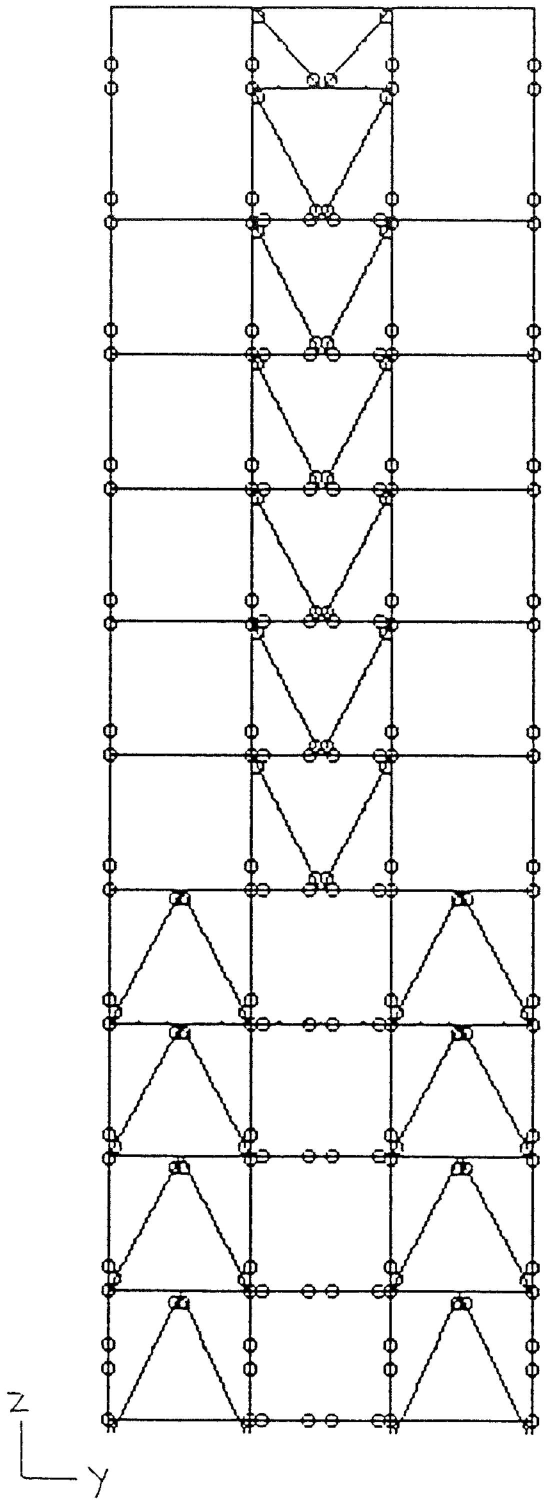


Fig. 2.15-b. Down-aisle direction

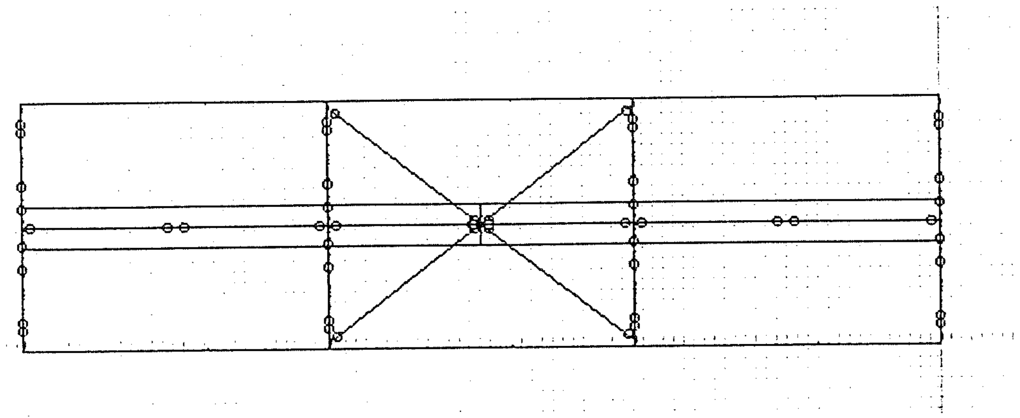


Fig. 2.15-c. Horizontal section

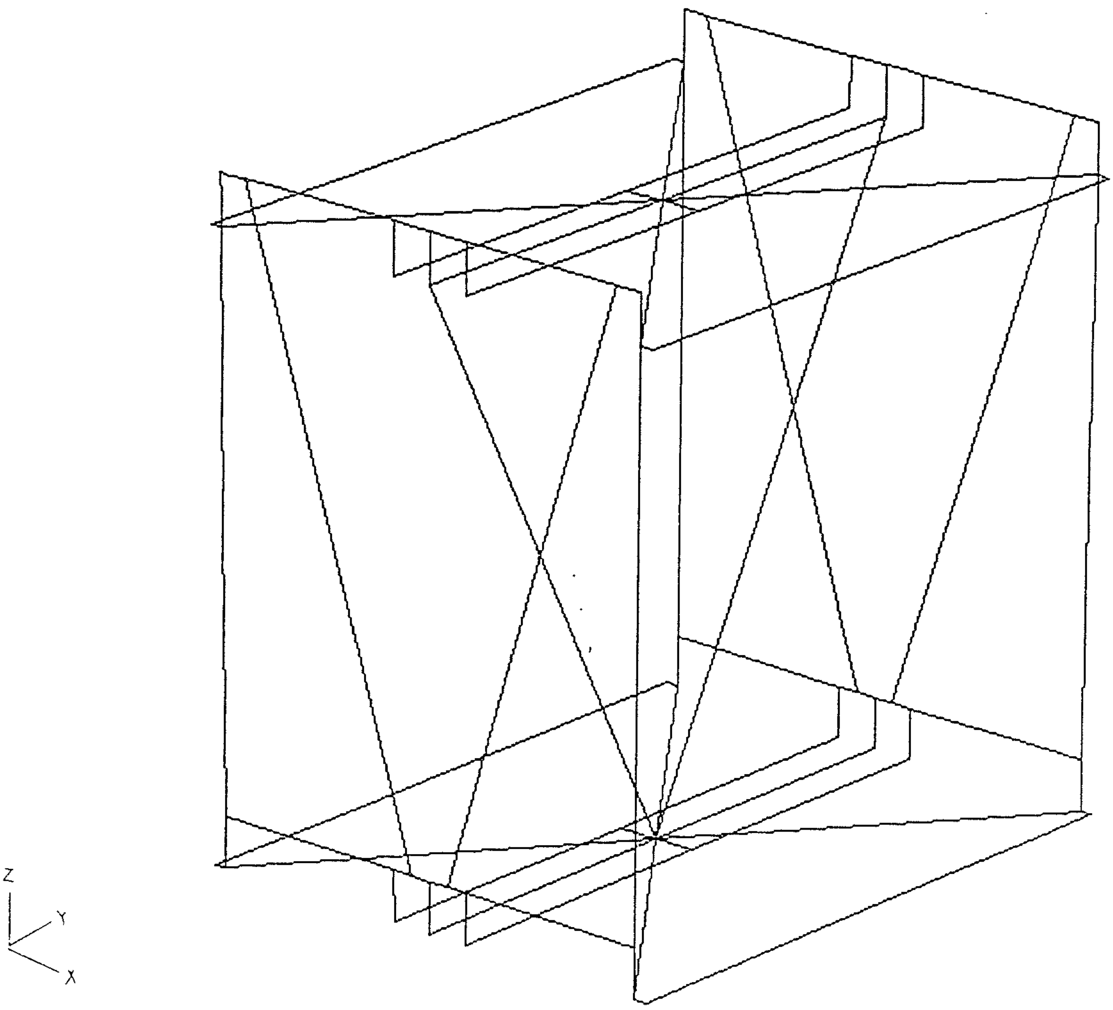


Fig. 2.15-d. Vertical down-aisle bracing system - detail

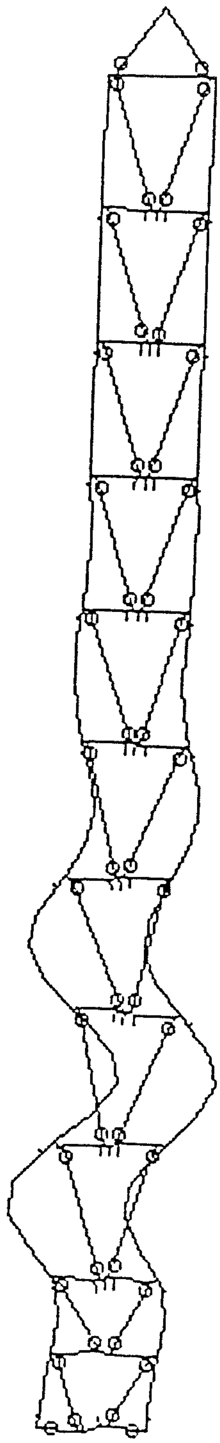


Fig. 2.16. Cross-aisle eigen buckling mode

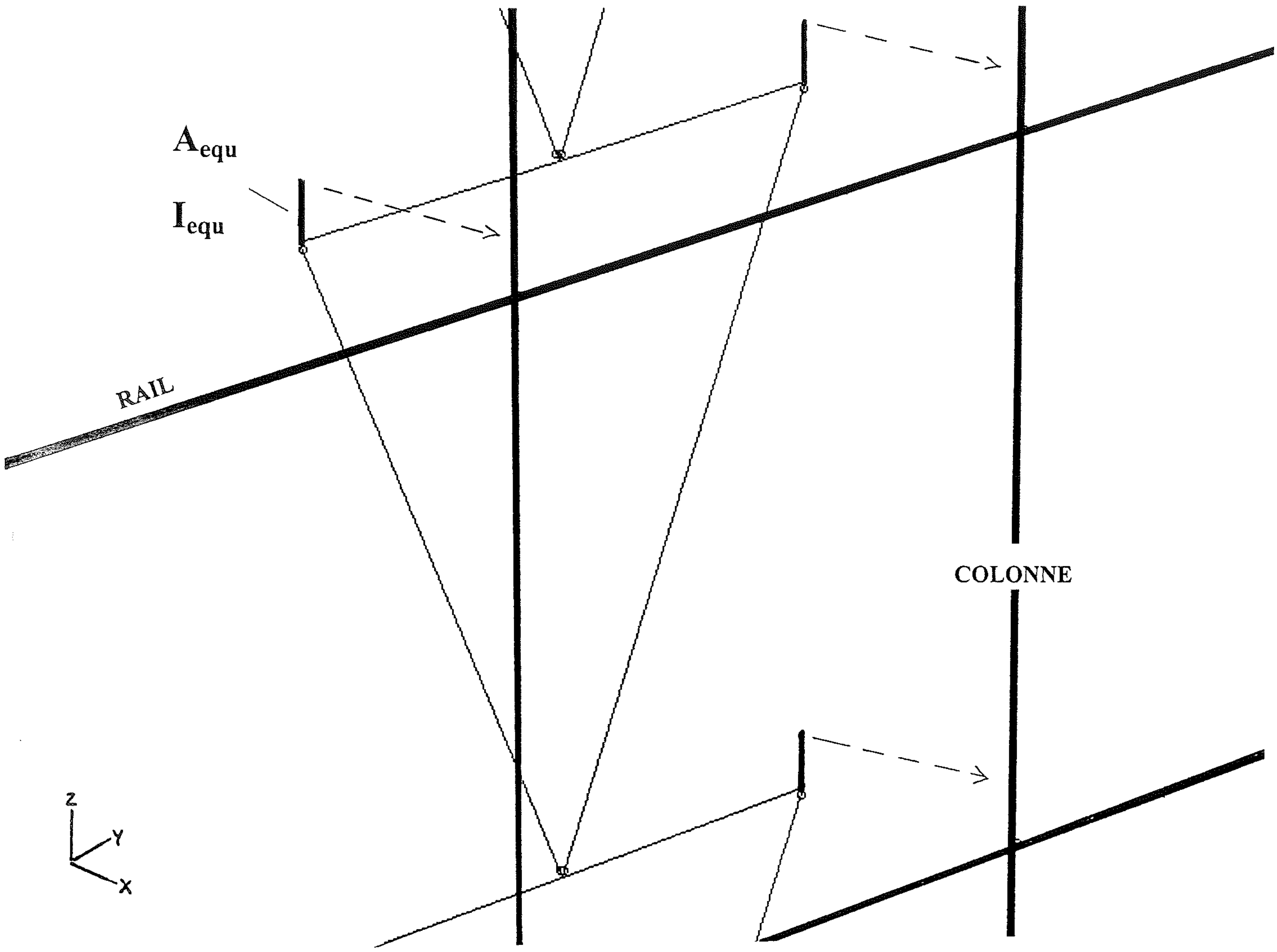


Fig. 2.17. Equivalent down-aisle 2-D model

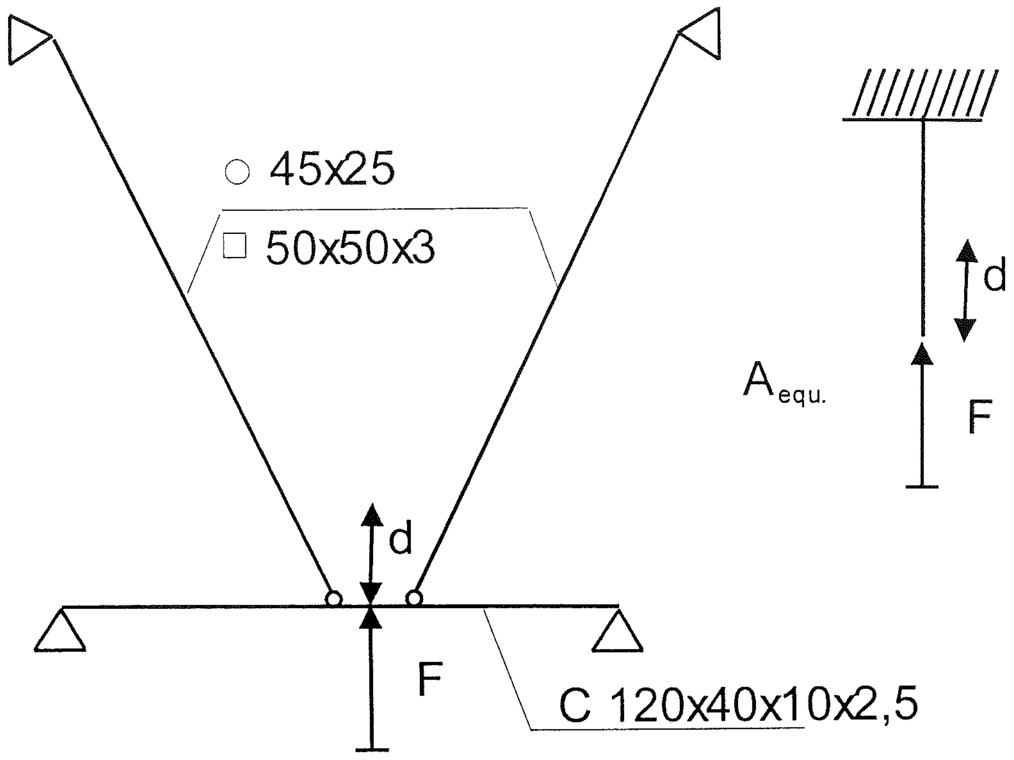


Fig. 2.18. Plane model for K_{vert} computation

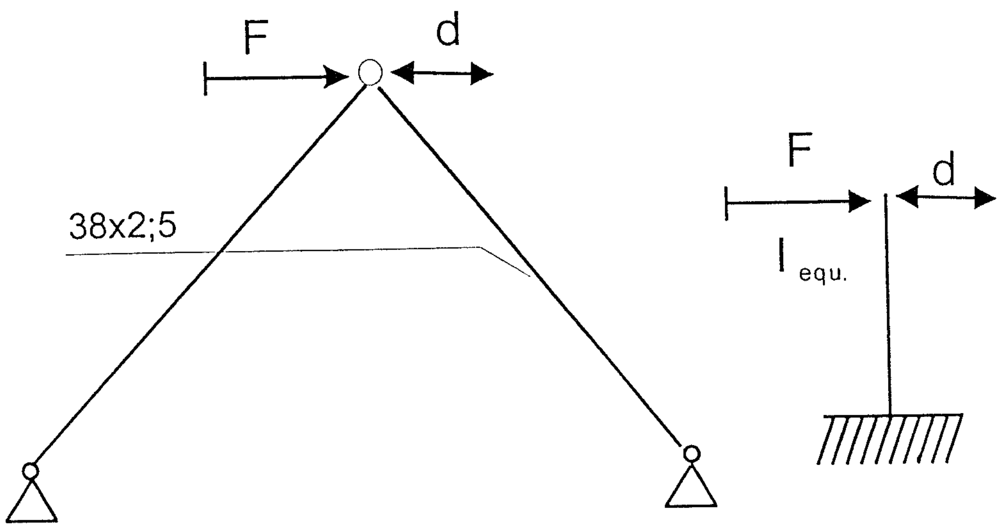


Fig. 2.19. Plane model for K_{oriz} computation

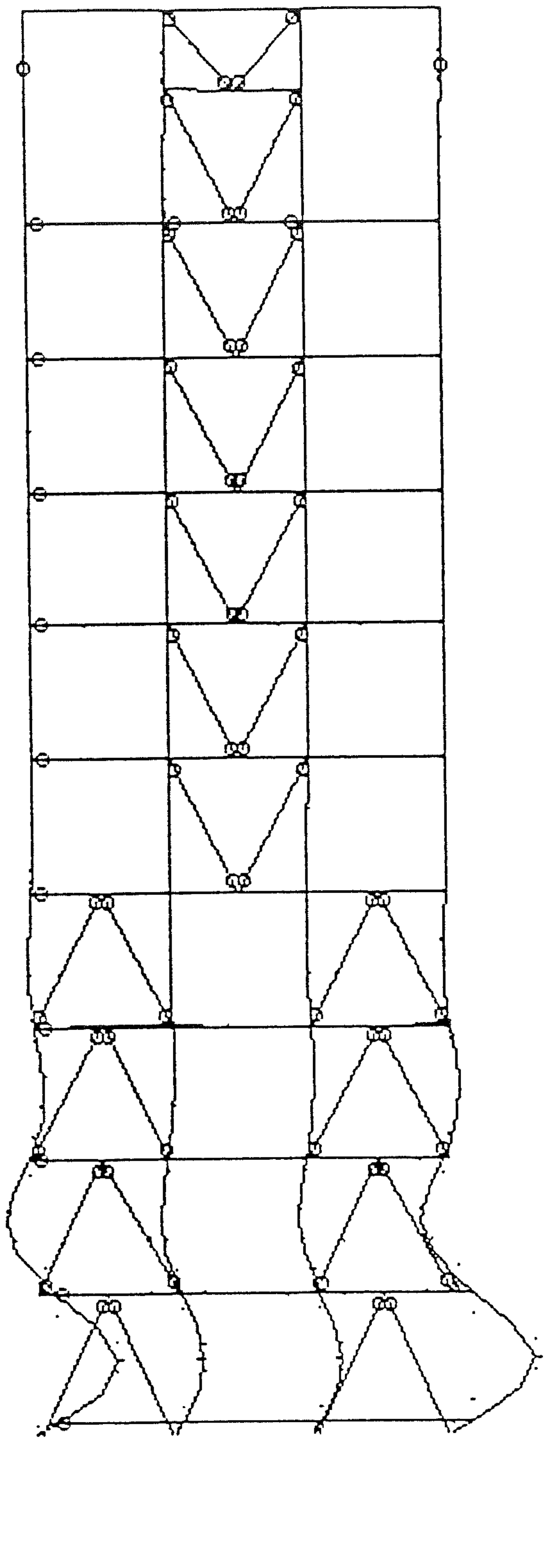


Fig. 2.20. Down-aisle eigen buckling mode for pinned connections