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Those peculiar structures in cold-formed steel: "racking & shelving"

One of the applications of cold-formed steel in which a considerable tonnage is involved is corrugated steel sheets for wall and roof cladding. Another is racking and shelving (R&S), those peculiar spatial steel structures used for economic and logistics-effective storage of goods in warehouses. R&S has to be flexible in use and therefore adjustable. It has to be competitive by providing mass production in combination with standardized components. The use of cold-formed steel members and components was already matter of course at the very first stage of the development of R&S products around World War 2. Flexibility in shape and material leads to cost-effectiveness in combination with special connections to realize adjustability.
Considering the non-traditional R&S detailing, the structural Eurocodes do not provide sufficient guidance to the rack designer for quite a number of design phenomena. Thus, the steel and racking industry, organized in the European Racking Federation ERF/FEM R&S, a member of the European Federation of Materials Handling (FEM), worked out a pan-European approach to the harmonization and standardization of R&S structural design and use. However, it took until 2008/2009 to have EN standards published, following the first FEM codes in 2000–2002.
For the cold-formed members and components typically used in R&S structures, insufficient analytical approaches are available, or they have to be validated by tests. "Design assisted by testing" is a substantial part of R&S structural engineering. With the publication of EN 15512 in March 2009 for adjustable beam pallet racking, a number of European testing laboratories were commissioned by the racking industry to conduct the obligatory testing, resulting in intensive collaboration between the R&S industry and "science", e.g. ECCS TWG 7.5. This paper gives an impression of R&S structures, the structural engineering challenge, the present state of the art and developments as well as the research still needed.

1 Racking & shelving (R&S)

Racking & shelving (R&S) is the collective term for the spatial (three-dimensional) steel frame structures for the storage of all kinds of goods. R&S allows storage in such a form that the warehouse volume is used in an optimal way in relation to the method of operation. Simple and cheap "block stacking" of, for example, pallets or containers directly on top of each other is not an option in many situations. The most cost-effective way of depositing & picking (D&P) is storage in such a way that each individual stored unit load can be directly approached, or is located behind only a small number of unit loads lane-wise per storage level.

A variety of racking types is available to suit the unit loads to be stored and the chosen way of handling. The most important ones are:

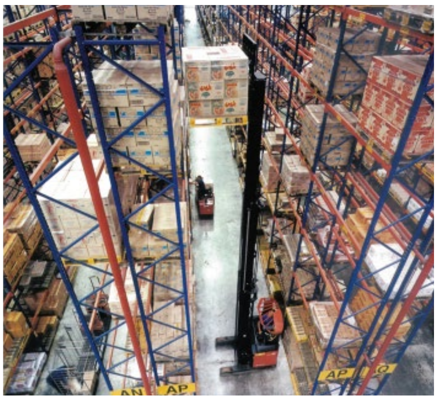


Fig. 1. Pallet rack operated by a reach truck (lift height up to approx. 12.5 m)

- Adjustable pallet racking (Fig. 1), and variations such as double-deep pallet racking
- Drive-in racking (Fig. 2)
- Dynamic storage (Fig. 3) and shuttle racking
- Cantilever racking (Fig. 4)

All such racking is intended for the storage of relatively large and heavy unit loads and is therefore used with industrial trucks, e.g. reach or very-narrow-aisle (VNA) trucks (Fig. 5), or a certain type of, in general, fully automated storage and retrieval (S/R) machines (e.g. stacker cranes, Fig. 6).

The options for small part storage are equipment such as (multi-tier) shelving, high-rise shelving, long-span shelving, open-face mini-load or shuttle mini-load racking. Shelving systems are intended for manual operations. Multi-tier shelving can have up to four tiers (levels) with a total height of approx. 10 m (see Fig. 7).

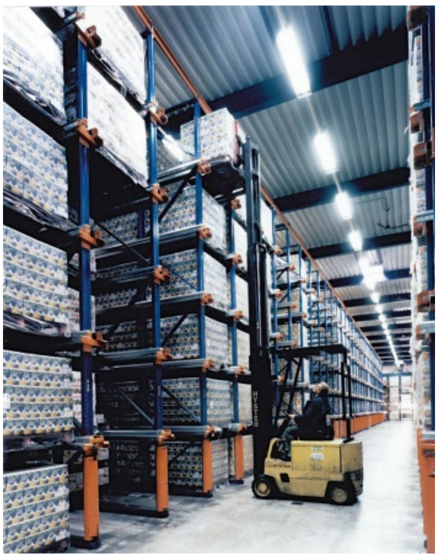


Fig. 2. Drive-in rack operated by a reach truck with side-shift

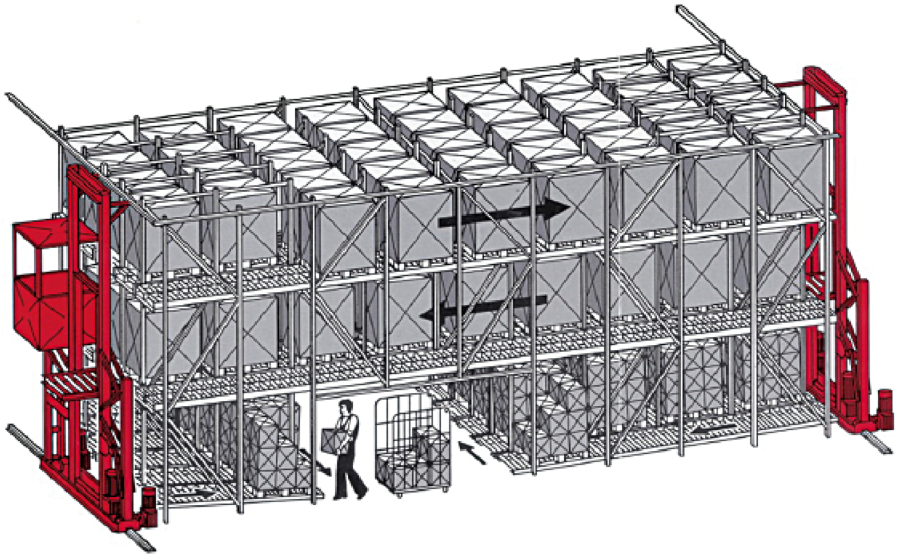


Fig. 3. Schematic view of hybrid (automated/manual) dynamic storage system

Fig. 4. Example of cantilever racking

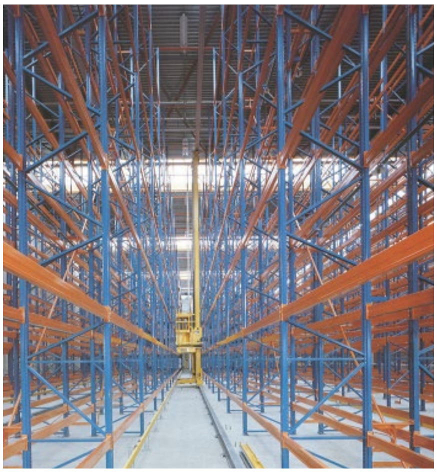


Fig. 6. Pallet rack operated by stacker crane

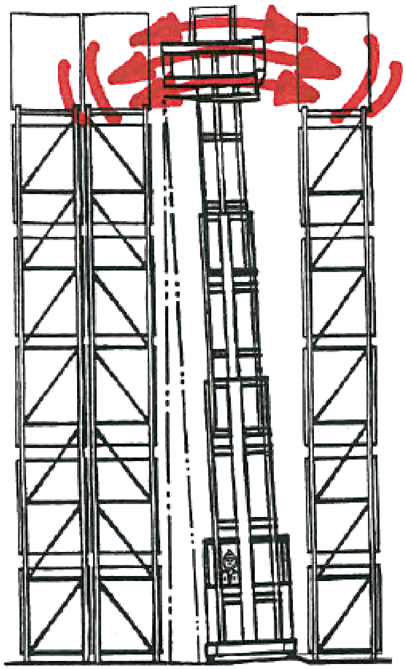


Fig. 5. Pallet rack operated by very narrow aisle truck: a) "man-up" operation, b) dynamic effects when travelling and lifting simultaneously

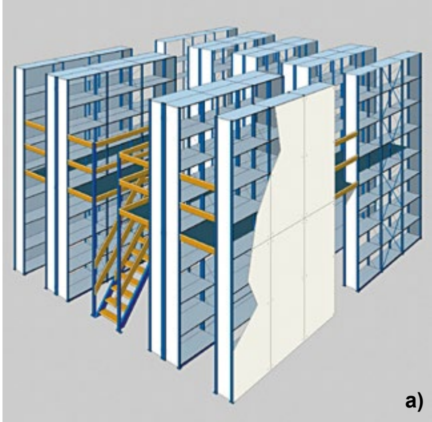


Fig. 7. a) Sketch of multi-tier shelving system; b) Example of 3-level multi-tier shelving

Adjustable pallet racking (APR) is the most common form, with heights of approx. 5 m to approx. 10 m. However, in conjunction with "high-lifting" reach trucks heights can reach approx. 12.5 m (Fig. 1), with VNA trucks up to approx. 15 m and when used with S/R machines up to approx. 30 m (free-standing) and even approx. 45 m (clad rack structure, see Figs. 8a and 8b).

The combination of that storage part of the logistics chain consisting of mechanical handling equipment (MHE: industrial trucks, S/R machines, conveyor systems, etc.), storage equipment (R&S, sometimes in combination with mezzanines or order-picking floors, see Figs. 9a and 9b) and warehouse management system (software package to support effective throughput and administration of stock control) is called a "storage system".

Flexibility in logistics is important because many rack parameters can change over time, e.g. types of goods and/or accessories on which goods are placed for storage (load make-up accessories such as pallets, box containers, bins, cartons, etc.), type of mechanical handling equipment (MHE, such as lift trucks and stacker cranes). Furthermore, the possibility of changing the configuration of the R&S, e.g. larger compartment heights, or moving the storage equipment to another warehouse are important conditions for the end user. Therefore, R&S, and sometimes mezzanines, too, have to be adjustable and relatively easy to disassemble and assemble again. These requirements have determined the specific design of R&S (Figs. 10–12) using prefabricated cold-formed steel components because of the flexibility in shape with cold-rolling (with continuous punching), press-braking or using a stage tool which for instance includes the subsequent cutting and bending to produce a component (e.g. beam end connector). To ensure maximum flexibility, steel rack structures include:

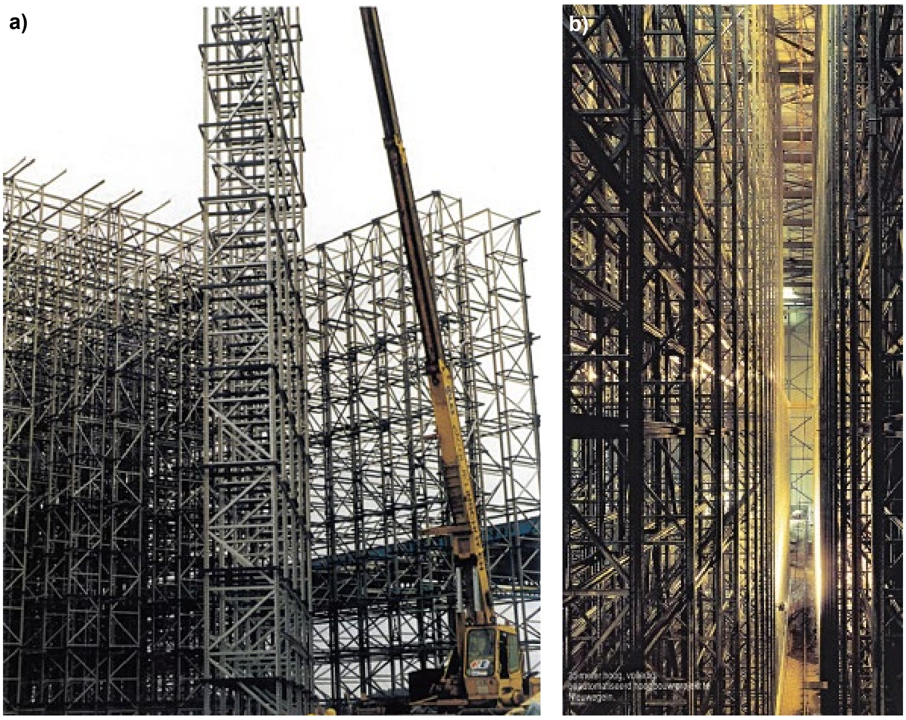


Fig. 8. a) Steel frame for a clad rack building; b) Steel frame for an in-house high-bay pallet rack (25 m high)

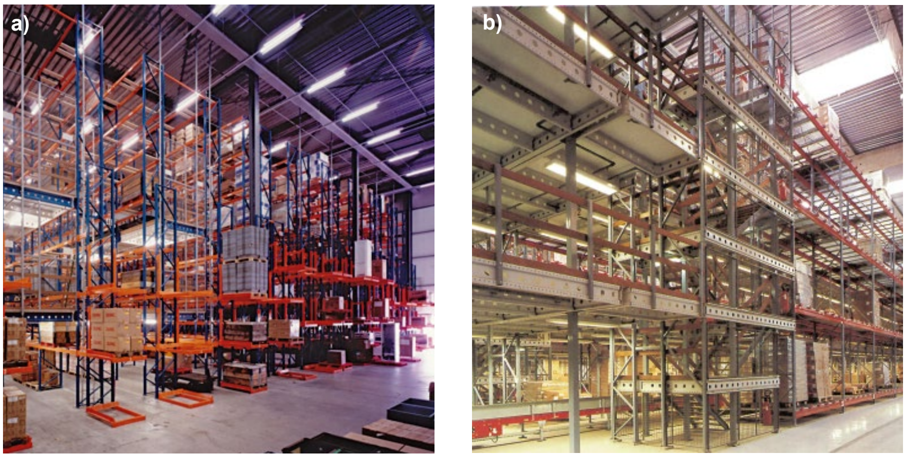


Fig. 9. a) Pallet rack operated by VNA truck, also supporting order-picking floors; b) Pallet rack in combination with order-picking floors

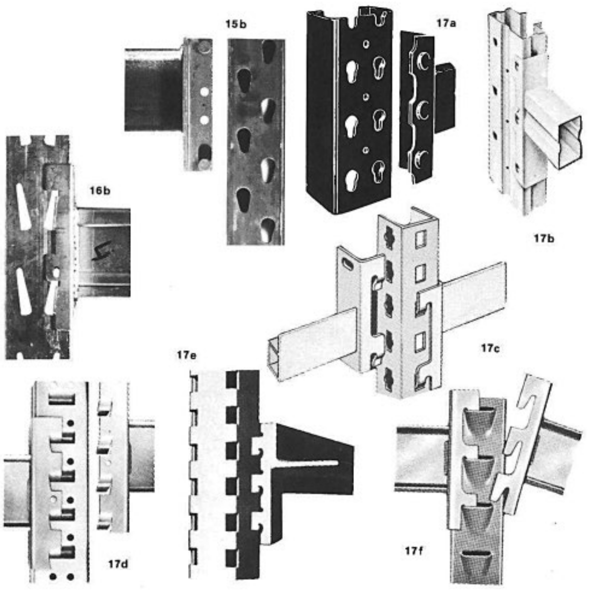


Fig. 10. Examples of combinations of pallet rack beam hook-in connections (fitted into upright perforations)

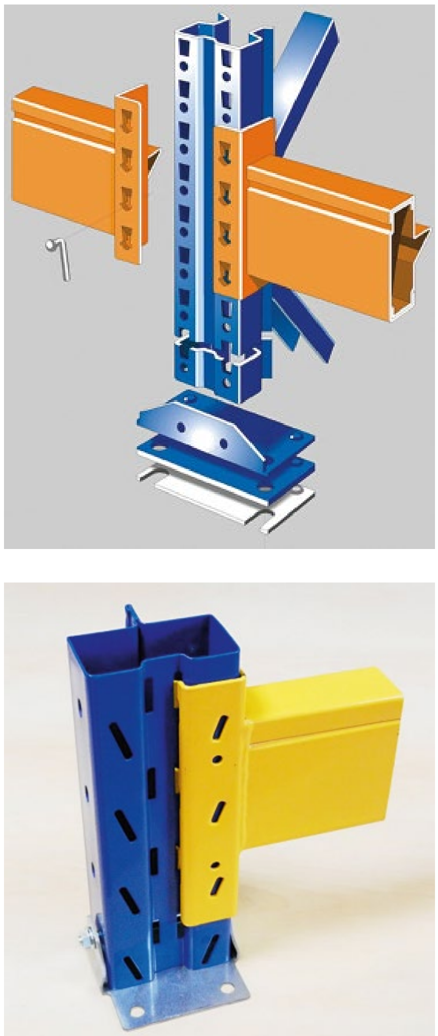


Fig. 11. Typical components of beam pallet racking – below an example of a ‘closed’ upright section

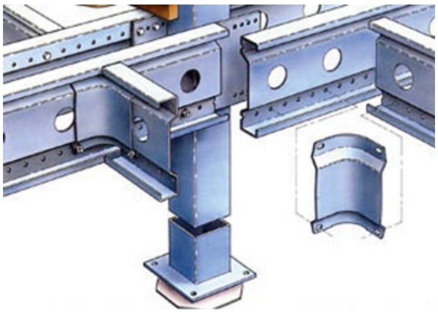


Fig. 12. Typical components of an adjustable mezzanine in cold-formed steel (floor panels mounted on beam grid)

- Specific connections (hooked or clipped in)
- Continuously perforated columns (called "uprights" in R&S)

It is obvious that the structural design of R&S will pose a challenge for every steel structure designer. Almost all fundamental, complex parts of Eurocode EN 1993 – Part 1-1 [1] and Part 1-3 [2] have to be considered, although these standards give insufficient guidance on racking structures. Therefore, additional specific design rules and extensive testing procedures are still necessary.

2 Specific design aspects for rack structures

R&S are serious loadbearing structures, much more heavily loaded than, for instance, the floors of office buildings. Heavy pallets, weighing up to 1000 kg or even 1500 kg, are stored above the heads of the persons working in a rack environment, e.g. order pickers and industrial truck operators. Safe structural design with the known mechanical properties of the non-traditional components and correct modelling of the actual physical behaviour is therefore of the utmost importance for de-

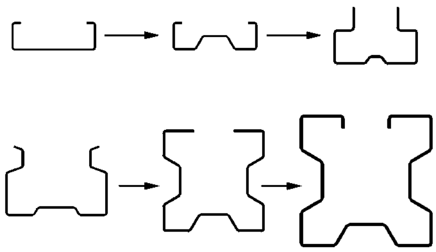


Fig. 14. Development of upright sections with higher load-carrying capacities because of reduced sensitivity to local and distortional buckling

termining the loadbearing capacity of these peculiar R&S steel structures.

At the same time, it is important to instruct the end user adequately about permissible forms of operation in order to ensure that daily use will not be in conflict with the design assumptions (see "Project specification and loading" below). In this respect, R&S differ from traditional loadbearing structures such as office buildings.

The most common rack type is "adjustable beam-type pallet racking", accounting for approx. 80 % of the racking market (shelving not included). Therefore, this article mostly focuses on pallet racking, preferably without down-aisle spine bracing due to the flexibility in the rack configuration (see Fig. 13). Down-aisle, semi-rigid frame bearing capacity is thus required.

All special phenomena influencing the strength and design of cold-formed sections and connections are relevant as well when designing pallet rack structures (see EN 15512, [3]):
- Thin-gauge open sections used for uprights may fail due to local, distor-

Fig. 15. Distortional buckling of an upright

Fig. 16. Torsional buckling mode of an upright

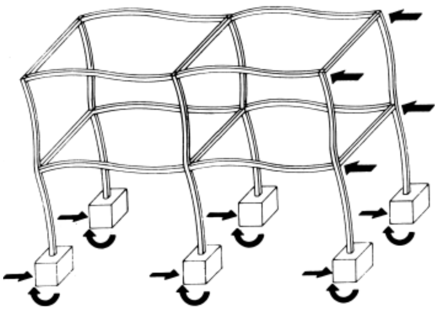


Fig. 13. Down-aisle sway frame behaviour of an unbraced pallet rack

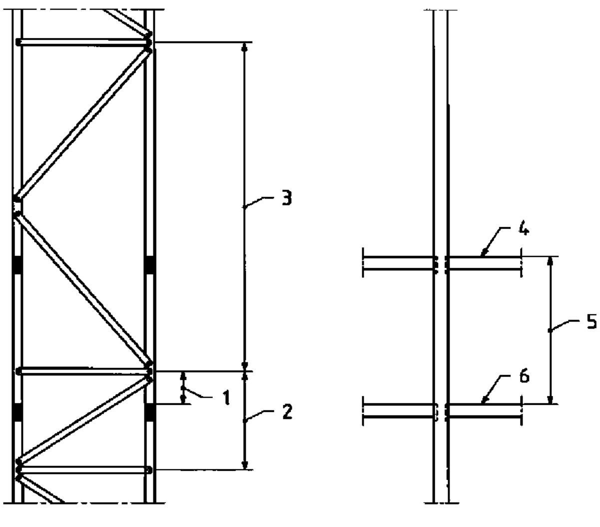
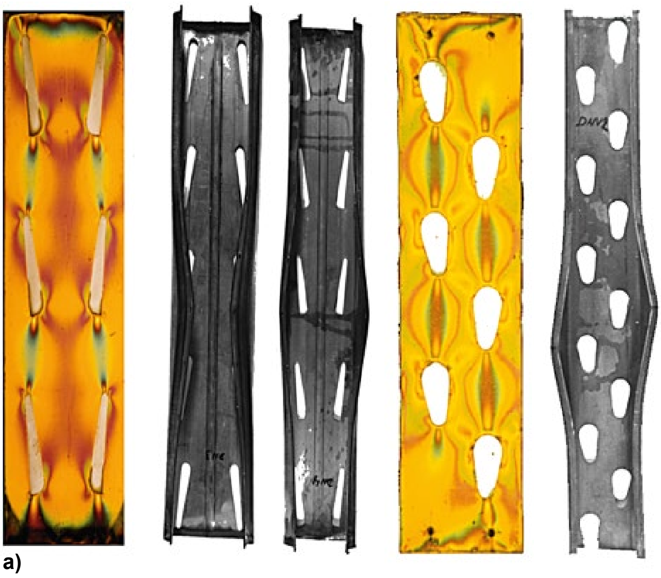
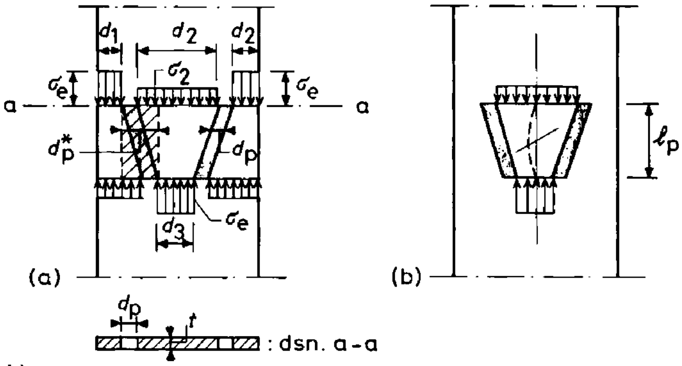


Fig. 17. "System Lengths" in pallet rack cross-aisle (left) and down-aisle (right) directions are not coincident


a)



b)

Fig. 18. a) Effect of continuous perforations and local buckling on the behaviour of a flat upright member; b) Effect of continuous angled perforations on the effective cross-section

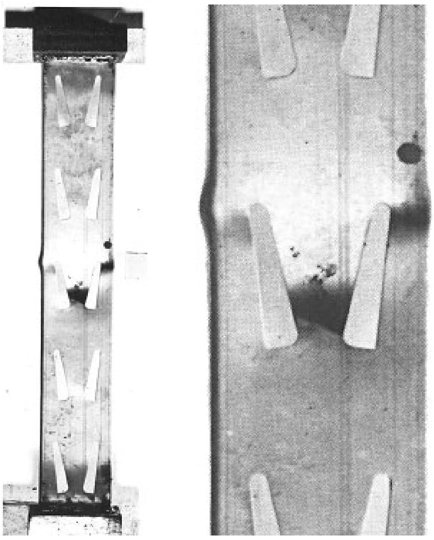


Fig. 19. Perforations affecting local buckling

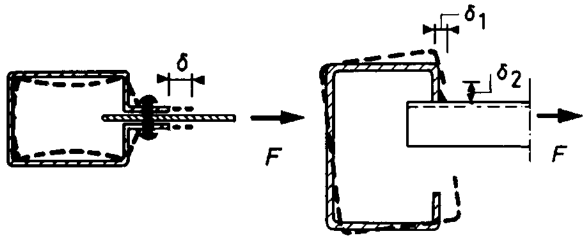


Fig. 21. Semi-rigid behaviour of shelving upright frame batten or diagonal to upright connection

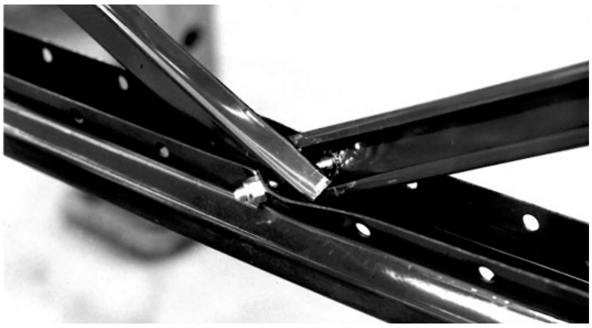


Fig. 22. Semi-rigid behaviour of pallet rack upright frame bracing member to upright connection

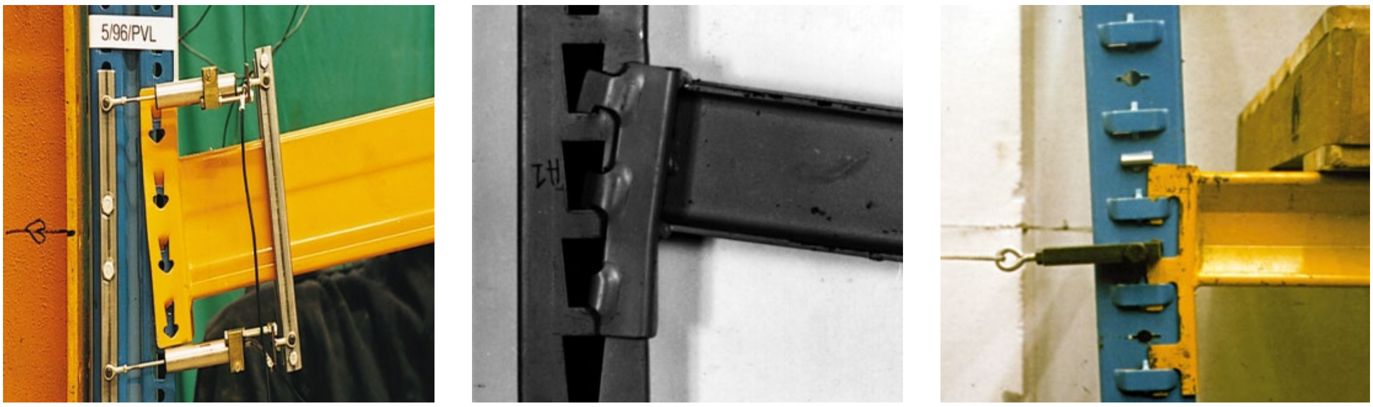


Fig. 20. Semi-rigid behaviour of connections between pallet rack beam and upright

tional and flexural-torsional buckling, or even in interactive combinations of these single failure modes (Figs. 14–16).
– Torsional-flexural buckling (TFB) of uprights in a pallet rack is calculated by combining down-aisle flexural buckling with torsional buckling restrained by the cross-aisle frame bracing node points. The "system lengths" to be used together in the down-aisle and cross-aisle planes have to be modelled (Fig. 17).
– Continuous perforations of uprights reduce column strength (Figs. 18–19).
– Non-traditional, flexible connections with semi-rigid behaviour are preferably used (Figs. 20–22).
– The beams are both loaded and stiffened by the pallets, e.g. concen-

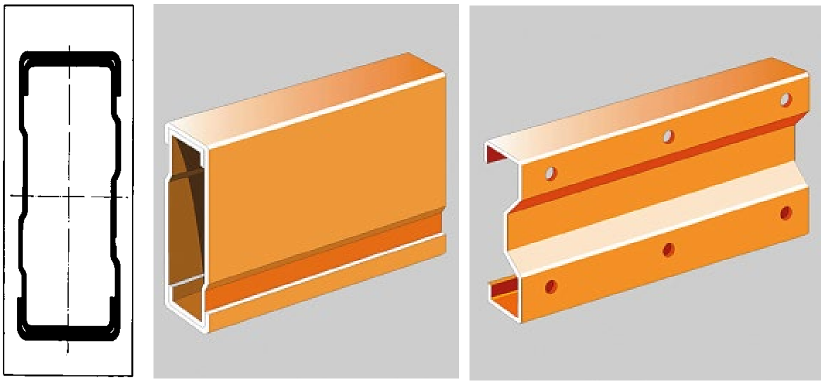


Fig. 23. Typical pallet rack beam cross-sections: 'boxed', nested C-beams (left) or sigma (Σ) beams (right) for automated operation with S/R machines

Fig. 25. Simulation of concentrated load transfer via the timber blocks of a pallet, causing additional crippling effects

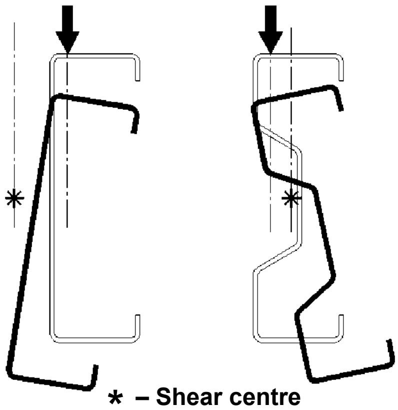
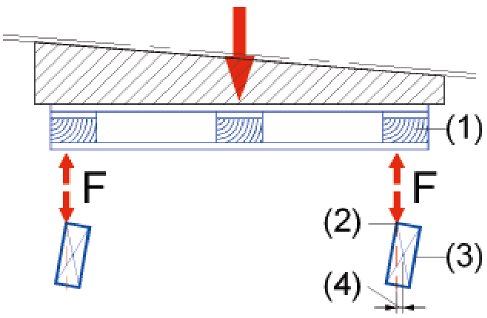


Fig. 24. 'Open' Σ-beams are also loaded in first-order torsion

trated load transfer via the timber blocks of a pallet, dynamics when depositing and retrieving a unit load, first-order torsion in the case of an "open" cross-section, possibility of lateral torsional buckling, (Figs. 23–27).

– Relatively thin base plates are used, thus influencing the rotational stiffness of the base plate connection as well as the performance under tension (Figs. 11, 28 and 29).

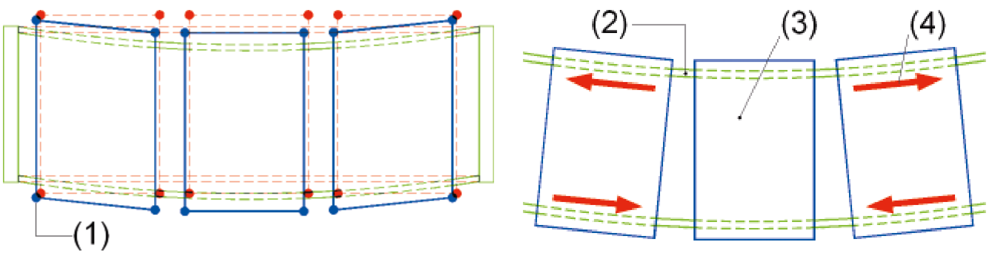
Pallet beams with an "open" cross-section are mostly singly symmetric Σ-beams, which are vertically loaded by the pallets and subjected to first-order torsion as well. Such beams are used, in general, in long-span shelving and in high-bay pallet racking operated in conjunction with automated S/R machines because the permissible beam deflection in automated systems is relatively small. The stiffness and strength/stability criteria will be closer to each other with 2-, 3- or 4-span beams. This is not possible with hook-in connections but, for example, with bolted beam-to-upright connections for which an "open" beam shape is practical. The loaded pallets have a positive rotational and lateral restrain-



(1) Pallet
(2) Load transfer at edge of beam
(3) Boxed (CC-)beam
(4) Distance between shear centre (SC) and edge of beam, positive when SC on right side

Fig. 26a. The bending stiffness of a pallet with goods generally acts as a restraint for beam torsion when (4) is positive

Fig. 26c. Design assisted by testing to determine ultimate load of Σ-beam, including all effects



(1) Pallet modelled with hinges: no diaphragm action
(2) Beam top flange displaced horizontally due to lateral flexural buckling
(3) Plan on pallet
(4) Diaphragm forces

Fig. 26b. The shear stiffness of a pallet with goods in the horizontal plane (diaphragm) acts as a restraint for possible beam lateral flexural buckling

Fig. 27. Design assisted by testing to determine the ultimate load of a secondary Σ-beam in a mezzanine beam grid, including the stabilizing effect of high-density chipboard floor panels

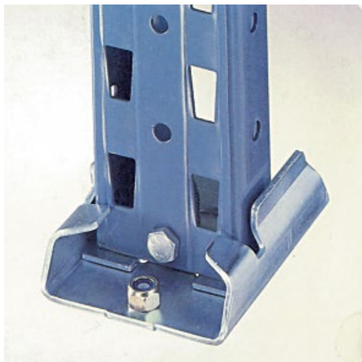


Fig. 28. Example of a pallet rack base plate

ing effect on the pallet beam because of their bending stiffness and diaphragm action (see Figs. 26a and b). The diaphragm forces are transferred from the pallets to the top side of the beams via friction, which makes the type of beam coating an additional parameter. Therefore, the design of pallet rack beams is regularly supported by tests (see Fig. 26c). The choice of a representative pallet type and quality is important.

For some rack types the position of the unit load on the beam is also important when determining the load-carrying capacity (see Fig. 30).

As in general pallet racking is not braced in the down-aisle direction (Fig. 13), owing to the adjustability and high cost-effectiveness required, any constraining effect with regard to sway stability has to be considered in the design. This also means including the rotational stiffness of the semi-rigid base plate connections, which mostly make use of non-anchored and often relatively thin plates (Figs. 28 and 29).

It is evident that the structural design principles and methods as they have been developed for traditional steel structures do not provide all the answers for R&S designers. Therefore, in addition to the structural Eurocodes ([1] and [2]), further design rules were and are to be developed, different to some extent for each type of racking. It is also evident that a designer of R&S should have sufficient expertise in the specific design of cold-formed structures. And it is also clear that "design assisted by testing" is a fundamental part of the structural design of R&S.

The R&S industry, in Europe organized in ERF/FEM R&S, has taken a number of initiatives in past decades and is still actively contributing to this speciality of steel design.

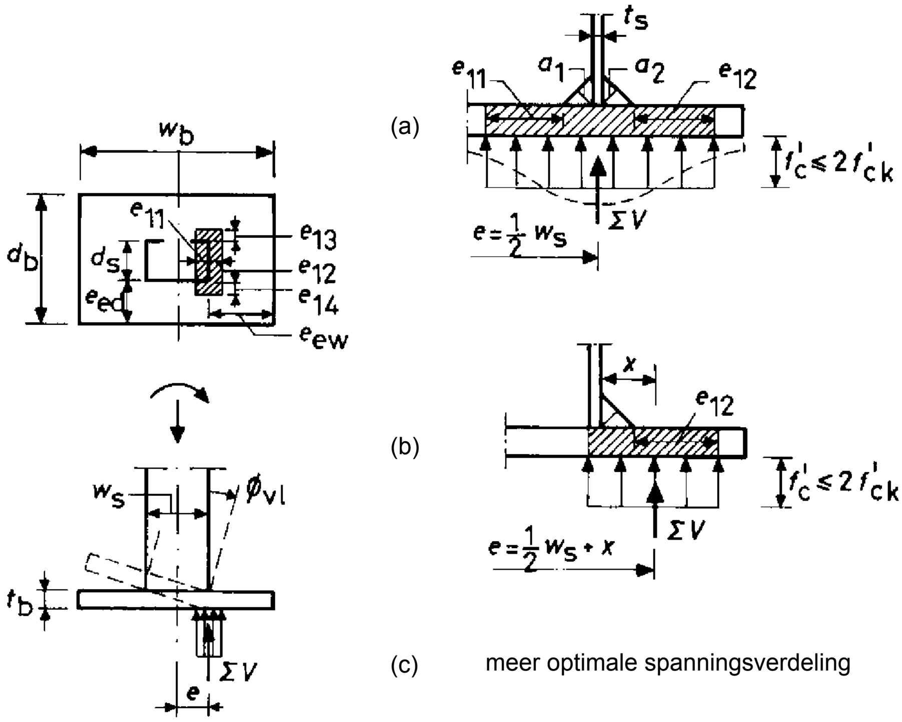


Fig. 29. Schematic drawings of load transfer from upright to concrete floor in the case of a relatively thin base plate

Fig. 30. Test setup for a drive-in rack beam ('beam rail') with a worst-case position of a simulated concentrated load transfer via a pallet 'timber block'

3 FEM and ERF/FEM – R&S

The Fédération Européenne de la Manutention (FEM) is the European Federation of Materials Handling Associations and was formed in 1953 (www.fem-eur.com). The FEM today has 13 national associations as members in the EU, Switzerland and Turkey and is the largest mechanical engineering sector in the EU. The FEM organizes its work into the following Product Groups:

- Industrial Trucks
- Cranes & Lifting Equipment
- Mobile Elevating Equipment

– Elevating Equipment
– Conveyors
– Intralogistics
– Racking & Shelving

The FEM Product Group "Racking & Shelving" was established in 1970 as Section X of FEM and today operates as the European Racking Federation (ERF). ERF's philosophy and that of its member associations and companies has always been to promote awareness and to support drafting of the specific design principles for rack structures, focusing on the following:

– The complexity of the structural design of R&S structures with regard to the mechanical properties of their typical components as well as their global behaviour.
– Interfacing the safety responsibilities of specifiers, suppliers and operators (Figs. 1–6) of R&S equipment; work is carried out between generally very heavy unit loads (e.g. loaded pallets with weights of 500–1500 kg) stored and retrieved by operators of industrial trucks at/from high storage levels (5–15 m).
– The need for the development of harmonized design standards for R&S structures to provide cost-effective solutions in a highly competitive market; it is also an important end condition for creating a level playing field in the industry.

4 Initiatives by ERF/FEM R&S: FEM codes and EN standards

A first attempt to have a European code of practice in place was already a main goal of a research programme funded by the European Community ([4]) in the early 1980s. Unfortunately, this first milestone was not adopted by the national associations of R&S manufacturers at that time; the time was not yet ripe for a European approach. This changed in the 1990s because the market was rapidly "Europeanizing" and "globalizing" (see [5]). Further, an accepted European design standard was needed to comply with legislation and responsibilities and for controlling corporate risks.

Therefore, ERF/FEM R&S decided to fund the development of appropriate FEM codes of practice over many years, culminating in 2002 with the publication of or ongoing work on (see also Tables 1 and 2):

– FEM 10.2.02 – Design of Static Steel Pallet Racking
– FEM 10.2.03 – Specifiers Guidelines
– FEM 10.2.04 – Users Code
– FEM 10.2.05 – Guidelines for working safely with lift trucks in pallet racking installations (draft/not published)
– FEM 10.2.06 – Design of Static Steel Shelving (draft/provisionally published)
– FEM 10.3.01 – Pallet Racking: Tolerances, Deformations and Clearances

For adjustable pallet racking (APR), all relevant FEM codes of practice were in place in 2002: structural design, layout and configuration design, project specification and safe use. This was a true landmark; after 20 years of talking and discussing, the European R&S industry had finally achieved an impressive level of harmonization on very important issues.

At the same time there was an awareness of substantially increasing throughputs in warehouses (more industrial truck movements per hour, higher speeds). Furthermore, demands with regard to legally defined responsibilities became more and more important. It was felt to be crucial that the ERF/FEM codes should be widely

Table 1. Review of standards in EN series "steel static storage systems"

First draft*)	EN standard		Published
FEM 10.2.02	EN 15512:	Adjustable pallet racking systems – Principles for structural design	March 2009
FEM 10.3.01	EN 15620:	Adjustable pallet racking – Tolerances, deformations and clearances	October 2008
FEM 10.2.03	EN 15629:	Specification of storage equipment	November 2008
FEM 10.2.04	EN 15635:	Application and maintenance of storage equipment	November 2008
–	EN 15878:	Terms and definitions	July 2010

*) The FEM codes with their commentaries are still available.

Table 2. Review of FEM codes of practice published, ongoing or planned

FEM code	Title	Published**)
FEM 10.2.05 draft/ not published	Guidelines for working safely with lift trucks in pallet racking installations	October 1999 (final: ???)
FEM 10.2.06 provisional	The design of hand-loaded static steel shelving systems	April 2001
FEM 10.2.07	The design of drive-in and drive-through racking	September 2012
FEM 10.2.08	Recommendations for the design of static steel pallet racks under seismic conditions	May. 2011
FEM 10.2.09	The design of cantilever racking	(mid-2013)
FEM 10.2.10 (FEM 9.841*))	Storage systems with rail-dependent storage and retrieval equipment – Interfaces	February 2012
FEM 10.2.11 (FEM 9.842*))	Rail-dependent storage and retrieval systems – Consideration of kinetic energy action due to a faulty operation in cross-aisle direction, in compliance with EN 528 – Part 1: Pallet racking	(mid-2013)
FEM 10.3.01-1 (FEM 9.831-1*))	Basis of calculations for storage and retrieval machines – Tolerances, deformations and clearances in the storage system Part 1: General, single-deep and double-deep beam pallet racking	October 2012

*) Drafted in liaison with the FEM Product Group "Intralogistic Systems"; their document numbering starts with "9".
**) Dates in brackets are target dates.

recognized and accepted by all parties involved in developing, building and operating storage equipment as part of the storage system. Therefore, ERF/FEM R&S took the initiative and strongly supported the route to convert the FEM codes of practice into formal European EN standards by funding the creation of CEN TC 344 "Steel Static Storage Systems" in 2002. It was felt that such a development would add credibility to the industry's basic philosophy of promoting safety in design and use as well as the structural engineering complexity of R&S structures.

Several EN standards for steel racks have since been published, see Table 1.

5 Project specification and loading

5.1 Loading in general

For warehouses, offices, etc. the variable loads acting on the structure and changing over time have been monitored and measured over many, many years, thus making statistical evaluations possible. This has resulted in national and European standards specifying, for instance, floor, roof, wind and seismic loads on buildings (see EN 1991, [6]). However, for R&S, the typical actions at the level of "characteristic loads" for an individual project are **not** a given statistical fact, instead have to be specified per project in combination with its daily operation. And those actions have to be monitored and controlled by the warehouse management during the system's operating lifetime to make sure they are not in conflict with the end conditions assumed at the design stage. The most important specific actions for storage racks are:

- Maximum weight of each statistical "family" of unit loads to be stored. In the event that differentiation in families or even within one family is not known or is not reliable, the design has to be based on the highest weight of unit loads to be expected during the design life and present at each storage location. Of course, possible pattern loadings have to be considered as well.
- Placement loads due to storage and retrieval activities.
- Forces induced by rack-supported and/or rack-guided S/R machines, e.g. stacker cranes.
- Loads on floors directly supported by the racking or shelving due to, for instance, order-picking activities, possibly with industrial pallet trucks, conveyor systems, storage of goods.

Considering the right actions in the structural design is of the utmost importance for ensuring safe operating conditions. Therefore, guidance was needed for the specifiers of the individual project-related design starting points as well for end users for daily operations. This resulted in EN 15620, EN 15629 and EN 15635, which are therefore an integral part of EN 15512.

5.2 Actions by lift trucks

Although much racking is served by industrial lift trucks, the above listing of actions does not include accidental forces due to possible lift truck collisions. The placement of loads given in EN 15512 reflects the likely result of good practice. But collisions are **not** considered in the design of racking operated by lift trucks, which is in contrast to, for example, the warehouse building columns, which according to EN 1991-1-7 ([7]) must be designed for a substantial accidental collision load of

5 × (sum of net weight of lift truck and maximum payload)
= (e.g.) 5 × (4000 kg + 1000 kg)
= 25000 kg (approx. 250 kN).

It is obvious that the cold-formed upright and beam sections commonly used in racking are not at all able to deal with such horizontal forces. To date it has never been part of rack design: pallet racking is not "truck-proof"! If this were to be the case, then the price per storage location would increase enormously and would affect the logistics industry in a serious way.

However, it is a fact that cold-formed steel racking structures can be operated safely although they are not "truck-proof". Based on this experience, the CEN/TC 344 committee has agreed to neglect EN 1991-1-7 for the design of pallet racking (see EN 15512 and EN 15635) on the condition that:

- Operators are trained and instructed to work in the rack environment concerned.

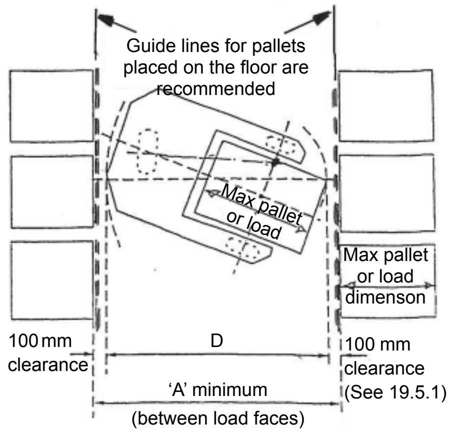


Fig. 31. Minimum rack operating aisle width required in the case of a 90° turning reach truck (FEM 4.005)

- Sufficient manoeuvrability for such skilled operators is in place in the form of, for example, sufficient rack aisle widths (see [8], for instance, and Fig. 31) and compartment dimensions (see EN 15620).
- Free-standing protectors are provided at all corners of rack aisles and passageways.
- The appointment of a person responsible for storage equipment safety (PRSES).
- Regular systematic inspections for collision damage and immediate unloading in the case of damage with a "red" risk level.
- Regular systematic inspection to ensure actual use is not in conflict with the user instructions/manual.
- A damage investigation procedure to ascertain potential causes with the intention of eliminating, or at least substantially reducing, the possibility of reoccurrence.

It is a fact that in most racking incidents, forklift truck collisions are involved, see Figs. 32 and 33. But it is evident that in cases of collapse the structural safety of the racking will generally be checked against the national legislation: health & safety and sometimes also the building regulations. It will therefore be obvious that it is an important responsibility of end users to maintain such conditions on a day-to-day basis, based on the supplier's operation instructions.

6 Responsibilities of specifiers, suppliers and users

In addition to the loading, the actual level of structural safety also depends

Fig. 32. *In the case of injuries or fatalities, the authorities are involved as well*

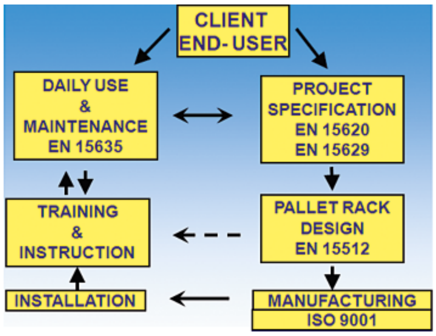


Fig. 34. *Scheme showing the important role of the client/end user in the interactive procedures from design to safe operation*

on the management system in place, which should ensure that actual operating procedures are not in conflict with the specified assumptions at the design stage. In the case of R&S, the "human factor" (operation and maintenance) is an additional factor affecting the actual structural safety at every moment in time. This is different to "normal" loadbearing structures, e.g. offices or the warehouse building in which the R&S is installed. It is for this reason that EN 15629 and EN 15635 also specify the responsibilities of all the players involved: specifiers with regard to the relevant project data and project requirements that must be complied with, suppliers with regard to the operation instructions on which the design is based, and end users, who must operate and maintain accordingly. The flowcharts of Figs. 34 and 35 (more formal for bigger projects) show that the final responsibility lies with the client/end user, who must comply with legislation, take care of the safety of his workers (and his stored goods) and achieve a satisfying logistics performance. And last but not least, it is also his investment (see also ERF Info Bulletin No. 1 [9]).

An additional responsibility for pallet rack suppliers in Germany and The Netherlands is compliance with their national A-Deviations as specified in Annex I of EN 15512.

7 Research

In the structural design of R&S, designers are confronted with the problems of cold-formed steel design and, in addition, with the specific characteristics of R&S, e.g. continuous perforated uprights and a variety of non-standard, semi-rigid connections, as described above. Moreover, each manufacturer produces different shapes and details for the various components. This makes it practically impossible to derive general calculation rules valid for a number of manufacturers. The consequence is that "design assisted by testing" is an integral part of R&S design. Quite a number of component tests are obligatory (see, for example, EN 15512, FEM 10.2.07, FEM 10.2.09).

The racking industry obviously considers EN standards as "more serious" than FEM industry codes of practice. After the publication of EN 15512 in March 2009, quite a number of R&S manufacturers decided to contact test houses or university laboratories with expertise in both the field of testing and test evaluation guided by EN 15512.

Performing such large test series enabled the testing laboratories to gain experience in the structural behaviour of racking structures and components, which resulted in a number of questions and ideas for more detailed descriptions or improvements as well as alternatives. The national industry was informed and, via the national R&S associations, ERF/FEM R&S as well.

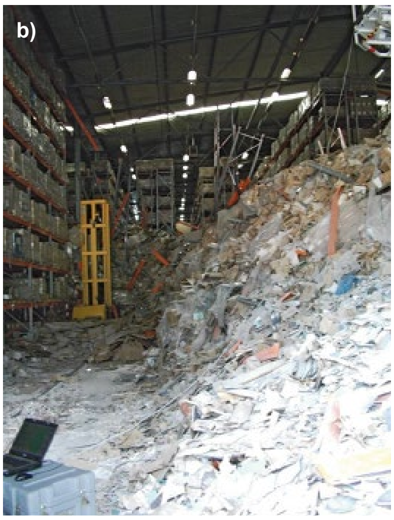


Fig. 33. *a) A minor collision can result in total collapse due to the dynamics of pallets falling; b) in many cases lift trucks are involved in collapses*

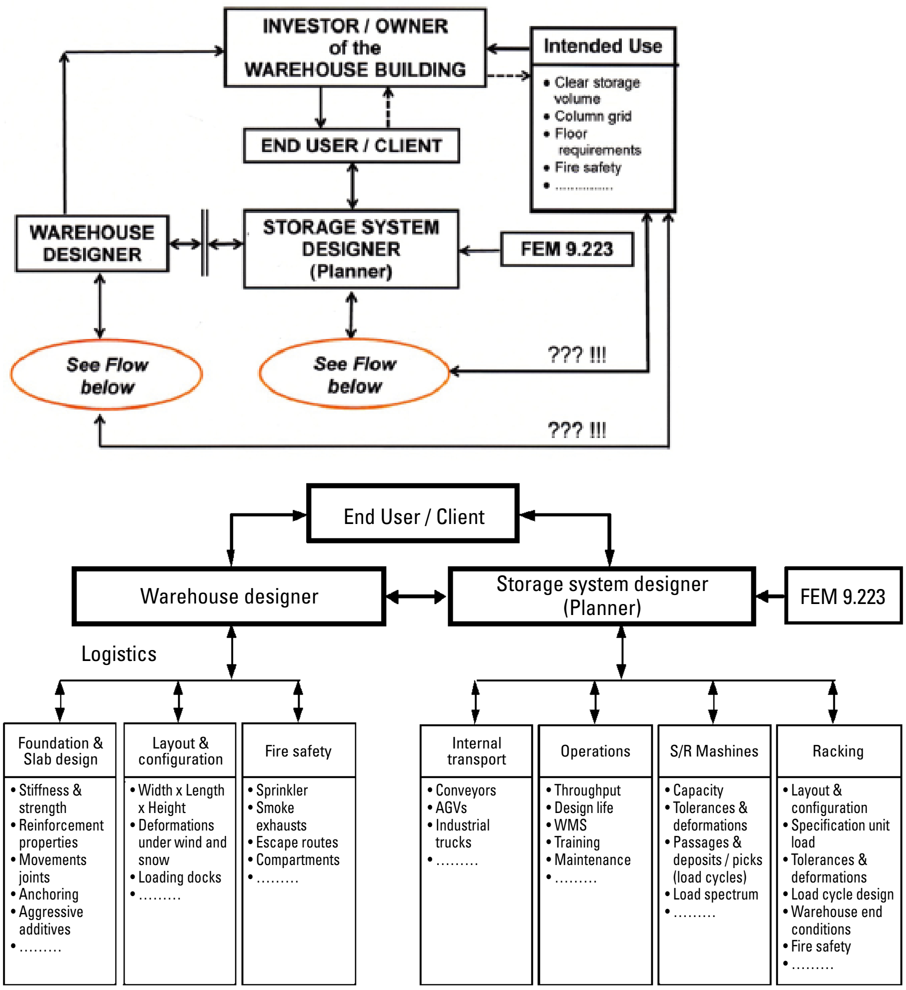


Fig. 35. "Ideal" warehouse design information flow (from FEM 9.841/FEM 10.2.10); (Typical example shown, but responsibilities can change or be shared, and contractual relationships are not indicated.)

ments in elasto-plastic finite element analyses, new developments in storage systems served by automated S/R plant (e.g. S/R machine supported by racking, see Fig. 36). One of the topics has been distortional buckling of perforated uprights [10] and an alternative test method for upright to floor connections [11].

Examples of current research items important or useful for the R&S industry:

– Elasto-plastic finite element analysis procedures to calculate the actual structural behaviour (deformations and stress distribution with increasing load until failure) of the R&S components concerned, as user-friendly as possible and to reduce the quantity of obligatory testing since test programmes are time-consuming and quite expensive, see [12], for example.
– Improvement of upright frame test procedures. There are different approaches (EN 15512:2009 [13] and [14] with load reversal and [15]). The consistency of test results, also when a certain play is present in the bracing node points, has to be examined.
– Fatigue behaviour of racking components supporting cranes for the cyclic load spectrum given by the

Three "Testing" workshops were organized in which both industry and testing bodies were involved.

Several representatives from the testing laboratories were also members of ECCS Technical Working Group TWG 7.5 dealing with the design of cold-formed members and sheeting in general. They came from the universities of Barcelona, Dortmund, Timisoara and Trento. Also the University of Cornell, USA, was involved. The racking industry was informed about fundamental research on R&S components discussed in ECCS TWG 7.5. This contact has resulted in cooperation between ECCS TWG 7.5 and ERF/FEM R&S.

In these intensive contacts between "science" and "industry", the inevitable discussions covered many topics, including today's design methods, arbitrary approaches with insufficient background studies, FEM codes and EN standards for rack types other than beam pallet racking, improve-

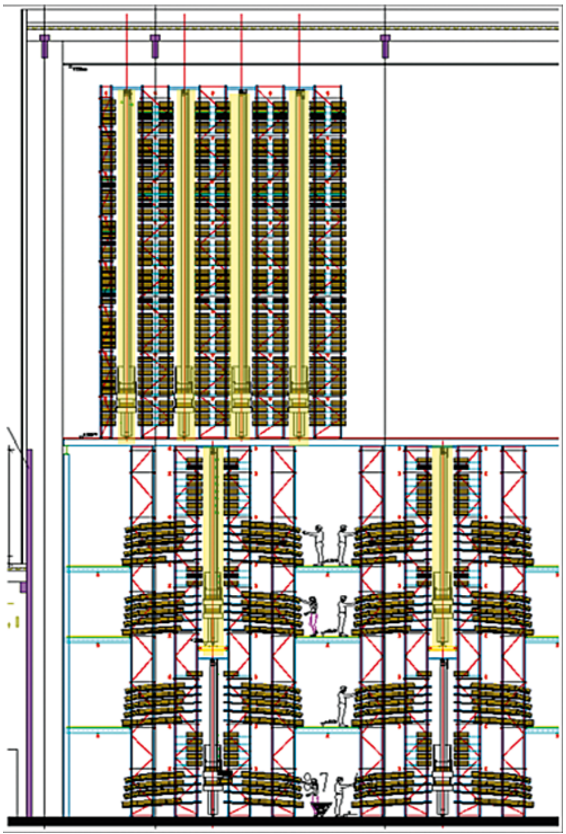


Fig. 36. Example of S/R machines at the 2nd level, supported by the rack

S/R machine concerned. This also has a **high priority** because knowledge of cold-formed sections (R&S: also continuously perforated uprights), components and their specific connections in relation to steel fatigue behaviour is very limited. Today, best practice decisions are made based upon EN 1993-1-9, but ongoing research has to fill this gap.
- Gaining experience from testing components of rack types for which an FEM Code was recently published, such as for drive-in racking, cantilever racking, multi-tier and high-rise shelving.
- A design method to determine the load-carrying capacity of pallet rack beams analytically, considering all phenomena as specified in EN 15512.
- Use of high-strength steel.
- Design with regard to fire safety. Requirements have to be defined (e.g. to protect fire-fighters outside, racking with stored goods should not collapse in the direction of an outer wall of a warehouse). Finite element analysis and load cases, including possible fire outbreak locations and pattern loadings (non-symmetrical), have to be considered.
- Investigation of the seismic behaviour of shelving systems as well as racking other than beam-type pallet racking. A current EC research project, SEISRACK II, is concentrating on the seismic design of steel pallet racks.

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