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A European Design Code for Pallet Racking

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Summary

The work leading to a European design code for pallet racking started almost 25 years ago. Many difficulties were encountered in the early days of this work. Notable were the absence of a consistent safety philosophy between the various countries of Europe and the existence of procedures with which the manufacturers were comfortable but which were potentially unsafe. There were also difficulties in defining acceptable standard test procedures.

The emergence of Eurocode 3, especially Part 1.3 dealing with cold formed sections, provided a new impetus to the work because here was a European code which provided the required basis for the design code. Accordingly, Section X of the Federation Europeenne de la Manutention (FEM) commissioned technical "experts" to draft the new code under the direction of its technical committee. It was a requirement that the code should be, as far as possible, compatible with Eurocode 3. In the early stages of the work, there were a group of these experts but, for most of the drafting period, only the authors of this paper were active.

The code was essentially complete in mid 1997 and, since then, it has been subject to trial use by the member companies of FEM and open to consequential comments. However, in May 1997, a significant meeting took place. FEM and the Rack Manufacturers Institute (RMI) of the USA sponsored a meeting between the first author and RMI's own "expert", Professor T Pekoz of Cornell University. The intention was to compare the two codes and to report on the potential for possible future harmonisation.

It emerged that the two codes were about as different as two codes covering the design of the same structural elements could be! However, the "experts" took a positive view of the situation and concluding that, from the technical point of view, there was no reason why the two codes could not be brought into convergence and that, in the meantime, we could each learn from the others experience.

Consequently, at this late stage in the evolution of the European code, a number of significant changes were made where it was considered that the European code could advantageously be made more compatible with the RMI code without in any way impairing its technical rigour.

This paper introduces the new European design code for pallet racking and compares and contrasts it with its American counterpart. As a pallet rack is a particularly demanding application of cold-formed steel sections, it is hoped that the designers of other cold-formed products may also learn from some of the approaches described in this paper.

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Introduction

In many respects, pallet racking represents one of the ultimate challenges in structural engineering design. A typical pallet rack may be viewed as being similar to a slender multi-storey building in which the beams and columns are cold-formed sections. Spice is added to the design process by the fact that it is fairly certain that the full design load will be achieved and there are no benefits to be obtained from secondary structural elements such as cladding and partitions.

Godley [1] has given an overview of UK practice which is also typical of the rest of Europe. In Europe it is usual for the beam-column connections to be clipped, as shown in Figure 1, in order to allow full flexibility in the selection of beam levels and to speed the process of erection. This has the result that the joints behave in a semi-rigid manner. It follows that unbraced racks are particularly sensitive to sway so that second-order effects play an important role in the design. Another consequence of this connection arrangement is that the columns contain regular arrays of perforations. Column design therefore usually requires consideration of a singly-symmetric, perforated open section carrying axial load together with bending about both axes.
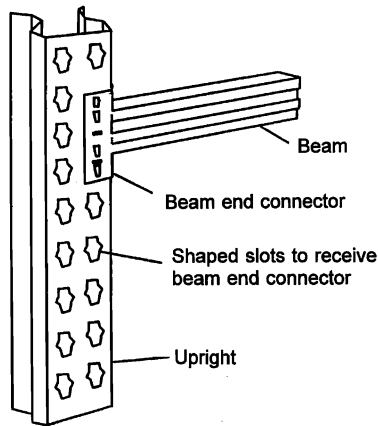
Fig. 1 Typical beam-column connection

Until recently, the best-developed design code was that produced by the Rack Manufacturer's Institute (RMI) in the USA [2]. This code is linked to the widely-respected American Iron and Steel Institute Design Specification [3] and both of these codes are regularly reconsidered and updated.

However, a good deal of work has been input in recent years by the Federation Europeenne de la Manutention (FEM) into the preparation of a European design standard for pallet racking and shelving linked to Eurocode 3 [4] . At the time of writing, after an extensive period in draft form for national comment, this document is complete [5] and has been approved for publication in October 1998 (after translation into the other European languages). It is much more complete and prescriptive than its American counterpart and contains a number of unique features. Some aspects worthy of particular note are discussed in the following sections.

Load and material factors

All European design codes are now written in limit state format and the one under consideration is no exception. This means that the fundamental design equation may be expressed as follows:

$$\sum \gamma_f \, F \le \frac{R_k}{\gamma_M}$$

where γ_f = relevant load factor
γ_M = relevant material factor
F = characteristic value of the effect of an action (load)
R_k = characteristic value of the resistance at the relevant limit state

The values of the load and material factors which are entered into the above equation are, of course, crucial to the safety and economy of the design and have been subject to a great deal of debate. Central to this debate is the consideration that the statistical variability of pallet loads is quite different from that of wind, snow and floor loads which constitute the primary live load cases considered in Eurocode 3. Another important principle is that the main uncertainty in the load-related performance of a pallet rack is in the interaction with the loading equipment. It is considered that these effects are more correctly incorporated in the accidental loads and placement loads than in the load and material factors. The following are the values that have finally been accepted by FEM:

Combinations of actions for the ultimate limit state

The design values of actions shall be combined using the following rules, whichever gives the larger value:

- considering only the most unfavourable variable action:

$$\sum \gamma_G \, G_k \; + \; \gamma_Q \, Q_{k,1}$$

- considering all unfavourable variable actions which may occur simultaneously

$$\sum \gamma_G \, G_k \; + \; 0.9 \sum_{i \ge 1} \gamma_Q \, Q_{k,i}$$

- design for accidental load

$$\sum \gamma_{GA} \, G_k \; + \; \sum_{i \ge 1} \gamma_{QA} \, Q_{k,i} \; + \; \gamma_A \, A_k$$

where G_k = characteristic value of a permanent action (dead load)
$Q_{k,1}$ = characteristic value of one of the variable actions
$Q_{k,i}$ = characteristic value of a typical variable action
A_k = characteristic value of an accidental action
γ_G = partial safety factor for permanent actions
γ_Q = partial safety factor for variable actions
γ_A = partial safety factor for accidental actions

Combination of actions for the serviceability limit states

- considering only the most unfavourable variable action

$$\sum \gamma_G G_k \ + \ \gamma_Q Q_{k,1}$$

- considering all unfavourable variable actions

$$\sum \gamma_G G_k \ + \ 0.9\gamma_Q \sum_{i \geq 1} Q_{k,i}$$

where the notation is defined above.

Load factors

The load factors γ_f are given in Table 1.

Load factor γ_f	Ultimate limit state	Serviceability limit state
Permanent actions γ_G		
• with unfavourable effect	1.3	1.0
• with favourable effect	1.0	1.0
Variable actions γ_Q		
• live loads	1.5	1.0
• unit pallet and shelf loads	1.4*	1.0
• placement loads	1.4	1.0
Accidental actions		
• γ_A, γ_{GA}, γ_{QA}	1.0	1.0

* If a crane-operated warehousing system includes for the weighing of all pallets and the rejection of all pallets weighing more than the design load of the rack, the load factor for unit loads may be reduced to 1.3.

Table 1   Load factors γ_f

Material safety factors

The material safety factors γ_M for ultimate limit state and serviceability limit state verifications are given in Table 2.

Material factor γ_M	Ultimate limit state	Serviceability limit state
Resistance of class 1, 2 or 3 cross-sections	1.0	1.0
Resistance of uprights and class 4 cross-sections	1.1	1.0
Resistance of member to buckling	1.1	1.0
Resistance of connections	1.25	1.0
Resistance of connections subject to testing and quality control (beam end connectors)	1.1	1.0

Note   For classification of cross-sections see section 5.3 of Eurocode 3. Class 4 cross-sections are those in which it is necessary to make specific allowances for the effects of local buckling when determining their moment resistance or compression resistance. In general, cold-formed steel uprights, because of all kinds of difficulties, should be considered to be class 4 but beams will generally fall within classes 1 to 3.

Table 2   Material safety factors γ_M

Placement loads

In contrast to the American code, the European code includes horizontal placement loads in both the down-aisle and cross-aisle directions. They are not intended to represent an impact load arising from misuse of the rack. They are loads which reflect the likely result of good practice in the placement and removal of loads from the system. These loads tend to have a significant influence on the design.

The crucial values are those for goods placed with manually operated mechanical equipment (fork lift trucks):

(1) For racks up to 3 metres in height, Q_{ph} is a load of 0.5 kN applied at any height up to the top of the rack.

(2) For racks over 6 metres in height, Q_{ph} is the worst case of either a load of 0.25 kN applied at the top of the rack or a load of 0.5 kN applied at any height up to 3 metres.

(3) for racks with heights between 3 and 6 metres, Q_{ph} is the worst case of a load at the top of the rack whose magnitude is determined by linear interpolation between (1) and (2) or a load of 0.5 kN applied at any height up to 3 metres.

Some rules are given for a conservative treatment of the above spectrum of loads whereby the number of load cases may be significantly reduced.

Second-order analysis of slender frames with semi-rigid joints

Pallet rack structures are probably unique in that they are framed structures that are regularly designed in such a way that the ultimate limit state may be close to the elastic critical load. This has required special consideration of the treatment of second-order effects and novel procedures have been devised to deal with this [6]. These are in harmony with the basic philosophy of Eurocode 3.

Crucial to the treatment of second-order effects is the necessity for a reliable estimate of the elastic critical load V_{cr} of the rack for failure in a sway mode. Two alternative methods are offered for down aisle stability and one for cross aisle stability. Frame classification is then based on the ratio V_{Sd}/V_{cr} where V_{Sd} is the design value of the vertical load on the frame.

(1)   If $V_{Sd}/V_{cr} \leq 0.1$, a frame may be classified as non-sway, i.e. its response to in-plane horizontal forces is sufficiently stiff for it to be acceptably accurate to neglect any additional internal forces or moments arising from horizontal displacement of the nodes. In such a case, a first-order analysis is sufficient.

Any other frame shall be classified as a sway frame and the effects of the horizontal displacement of its nodes taken into account in its design. Unbraced racks are invariably classed as sway frames in the down-aisle direction and therefore require consideration of second-order effects.

(2)   If $0.1 < V_{Sd}/V_{cr} \leq 0.3$, a level 2 analysis may be used in which second-order effects are treated approximately (eg according to Reference [6]).

(3)   If $V_{Sd}/V_{cr} > 0.3$, a level 1 analysis is required in which second-order effects are treated directly.

Note: The limit at which an accurate second-order analysis becomes mandatory is more generous than that in Eurocode 3. This is because pallet racks have semi-rigid joints and generally have a regular construction. In these circumstances, the agreement between the exact and approximate methods is much improved so that the range of validity of the approximate methods may be increased.

Testing philosophy and the treatment of test results

Design philosophy

The European design code is based on a philosophy of rational analysis assisted by testing. The market for storage products such as pallet racking is highly competitive and efficient structural performance is at a premium. This can often be most easily achieved by testing

critical components which are difficult to analyses or whose analysis may rely on conservative assumptions in order to ensure that acceptable standards of safety are maintained. Thus, the primary purpose of testing is to provide the designer with realistic information about the performance, usually strength and stiffness, of components of the structure.

Quality assurance

However, testing is also used to provide quality assurance during production and, for this purpose, two tests are specified. These are perceived to be crucial to the maintenance of quality in production. The structural performance of pallet racks is heavily dependant on the behaviour of the connection between the beam and the upright, usually termed the beam end connector in European parlance. This is particularly so in the case of unbraced racks which form the majority of installations. Hence, manufacturers are required to make tests on these connections on a regular basis as a part of their quality assurance. Tool wear, variation in material properties and detailed design changes are all seen as potential causes of significant change in the mechanical performance of the beam end connector which thus requires regular monitoring.

The second quality assurance test is only of concern to those manufacturers who use the enhanced mechanical properties obtained by cold reducing steel strip prior to perforating and cold rolling. It is well known that cold reducing can substantially increase the yield stress of a carbon steel and that this increase is at the cost of a reduction in ductility to levels which may be below those that are generally specified in recognised standards. In order to ensure that such material is suitable for the manufacture of the components of pallet racks, a tensile test is used to determine the yield stress accompanied by a bend test designed to ensure that the ductility of the cold reduced material remains adequate.

Overview of test regime

In addition to these quality assurance tests, the European design code lists a total of 13 tests which may be used in the design of pallet racks. Of these, 9 are mandatory in some or all circumstances. Table 3 shows a list of these tests and the conditions under which they may be compulsory.

Tests on uprights

Three of the tests in Table 3 are compression tests on uprights. The stub column test is made in order to determine the effective area of the perforated upright and may be carried out in one of two alternative ways. In the first, a short length of upright section is loaded in compression through ball bearings which provide a pinned connection with a well-defined line of action of the load. This approach, which is the traditional way of carrying out the stub-column test in Europe, requires that the optimum line of action of the load be determined by a process of trial and error. The alternative method is to test between flat ends using an arrangement similar to that specified by the RMI [2]. Recent research by Pu et al [12] shows that the two methods give nearly identical results.

In the second set of upright compression tests, the stub column test series is extended to allow a column curve to be determined experimentally. Pallet rack systems normally employ braced frames with a fixed gate and these tests are made on a range of upright lengths in increments of a half or a full bracing gate depending on the bracing pattern. The merit of

this set of tests is that a column curve may be derived which takes account of the effects of the torsional restraint provided by the frame bracing and its connection to the uprights as well as the out of plane buckling effects. The test information allows the determination of the effective cross-sectional area as well as the column curve.

Test No.	Title	Status
1	Materials tests	Mandatory[*]
2	Stub column tests	Mandatory[**]
3	Compression tests on uprights	Non-mandatory
4	Distortional buckling check	Mandatory
5	Bending tests on beam end connectors	Mandatory
6	Looseness tests on beam end connectors	Mandatory[***]
7	Shear tests on beam end connectors	Mandatory
8	Tests on floor connections	Non-mandatory
9	Tests for shear stiffness of frames	Mandatory
10	Bending tests on upright sections	Mandatory
11	Bending tests on beams	Mandatory[†]
12	Tests on upright splices	Non-mandatory
13	Impact tests	Non-mandatory

*	Mandatory only for steels with no recognised mechanical specification.
**	Mandatory for perforated sections only.
***	Mandatory unless the bending test on beam end connectors is carried out using the portal test so that the looseness is incorporated in the moment-rotation relationship.
†	Mandatory only in respect of beams of open cross-section which are not symmetrical about a vertical axis.

Table 3   Tests specified in the European design code and their status

If, alternatively, the column curve is deduced from the stub column tests without any further testing, there is a risk that any distortional buckling effects which may be present could be ignored. Many pallet rack uprights, because of their relatively wide unstiffened or partly stiffened flanges, appear to be particularly susceptible to distortional buckling effects. In these circumstances, a check for distortional buckling is mandatory and is made by testing a column equal in length to a single bracing panel, normally about one metre long.

Such columns generally fail in a torsional flexural mode of buckling but, if distortional buckling occurs the failure load will be reduced. In this test, the average failure load observed in the tests is compared with the failure load for the observed mode of failure calculated on the basis of the effective area determined by the stub column tests. If the test results lie below the predicted values, the effective area of the section is reduced proportionately. This is a simple method of adjusting for the effects of distortional buckling and avoids the need to test a large number of uprights of different lengths, because the now modified effective area may be used with the normal design curves for uprights over the whole range of lengths.

Tests on beam end connectors

Another group of three tests is concerned with the performance of the beam end connector. The critical properties of the connector are stiffness, bending strength and looseness. Shear strength is also important and a simple test is specified for this. However, for many connectors, shear strength is not often a limiting factor.

The bending characteristics and looseness of the connector may be measured either by separate tests on a simple cantilever arrangement as shown in Figure 2 or by a portal frame test similar to that described in the RMI code [2]. The European code requires that all combinations of beam section, upright section and connector type shall be tested unless it can be shown that the results can be reliably predicted by interpolation.
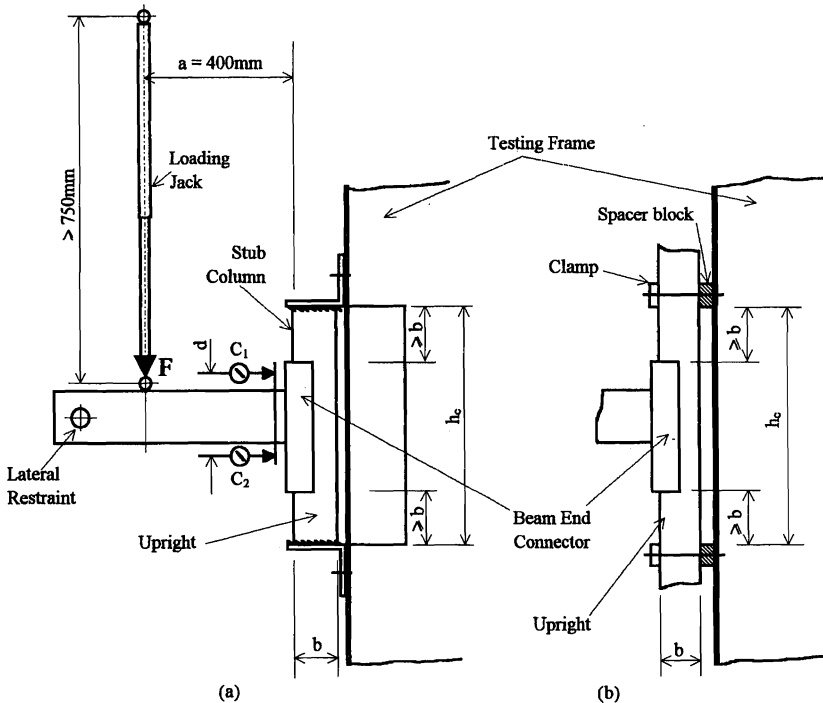

Fig. 2 Cantilever arrangement for the beam end connector bending test showing alternative methods of support for the upright

The looseness of the connector is a significant factor in the design of unbraced pallet racks because it contributes towards the frame imperfections. These must be taken into account in the design. The idealisation that is made for the effect of looseness is that the unladen rack is free to adopt an initial out-of-plumb position equal to the angular looseness of the connectors. Practical experience indicates that this is a little unrealistic because it presupposes a degree of uniformity of configuration and this may not be present. In practice there is a

range of loosenesses present in any batch of connectors in a given rack and the effects of small errors in the way that the connector is welded to the beam, the lack of straightness of the members of the rack and errors in the pitching and grouping of the perforations all tend to mutually interfere and suppress the slackness in the rack which is the consequence of this idealisation.

For many designs of connector, looseness is significant but small and the effects of this idealisation are not critical. However some connectors exhibit considerable looseness and systems using such connectors may be unreasonably penalised by the adoption of the idealised looseness model. Consequently, the portal frame test shown in Figure 3 provides an alternative approach in which the effects of any looseness are subsumed in the test for connector stiffness and strength.
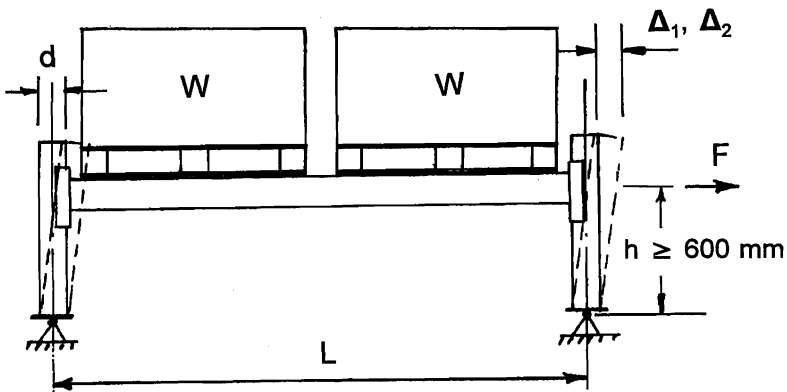
Fig. 3 Portal frame arrangement for beam end connector bending and looseness tests combined

In the portal frame test, a horizontal load is applied after the beams have been loaded with their service loads. Deflection measurement begins before any loading takes place. The effect of differential connector looseness will be observed as the rack sways into an equilibrium position under vertical load. As the test progresses and the horizontal load is increased, the bending moment in one connector will reverse. If connector looseness is present, its effect should be noticeable as a reduction in the slope of the load deflection curve while the connection is loose and until it reverses. The consequence of this is that the apparent stiffness of the connector will be reduced.

The portal frame test is likely to be more costly in time and material than the cantilever test for connectors, but it is left to the manufacturer to decide whether there are any benefits to be gained from testing connectors in this way.

Tests on floor connections

The connection between the upright and the floor may be assumed to be pinned, in which case no tests are required. However, because pallet rack structures are often very slender, any stiffness at the base can have a considerable beneficial effect on the overall stability of the

structure. An optional test on the floor connection is described which measures its stiffness and strength. A characteristic of this connection is that both stiffness and strength are dependent upon the axial load in the upright so that the test must be repeated at representative values of the axial load.
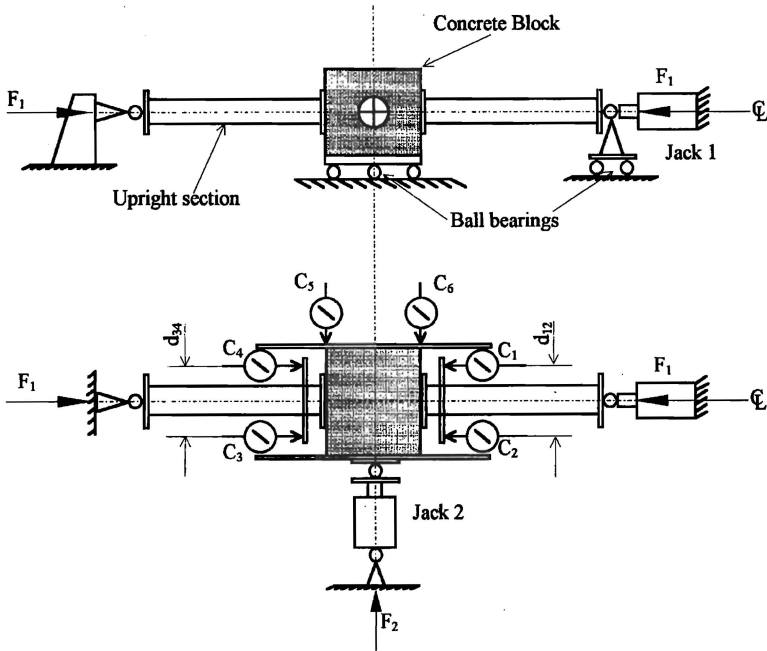
Fig. 4 Test arrangement for floor connections

The test arrangement is shown in Figure 4. In the test, the axial load is held constant while the lateral load is increased until failure occurs. The bending moment at the base and the relative rotation of the upright and the base are measured. The connection has both stiffness and strength whether or not holding down bolts are used because of the flat end of the column base. When holding bolts are not included, the test becomes very unstable at the point of failure.

Other tests in the European code

Tests on upright splices are necessary if the upright splice is treated analytically as anything other than a pinned connection. They are made in a similar manner to the tests on the floor connections.

The shear stiffness of the upright frames is important in determining whether a tall narrow frame is susceptible to overall buckling in the cross-aisle direction. The shear flexibility of such frames derives from the axial flexibility of the bracing elements and from the connections between these and the uprights. In some cases, the flexibility of the connections

is the dominating factor. The test is a simple one and is necessary because the effects of joint flexibility and member eccentricity are difficult to calculate accurately.

The bending strength of upright sections is determined by test because of the difficulty in estimating the combined effects of the perforations, local buckling and of the torsional restraints provided by the frame bracing. The test is carried out on a frame assembly in four point bending.

Finally, a test procedure is included to check that the beam end connector will operate satisfactorily at low temperatures such as in cold stores. The test is a Charpy type test and is a shear test on a connector or a hook from a connector. This test is made over a range of temperatures in order to determine the transition temperature at which the component becomes brittle. Some manufacturers have experience of this test, but it is not mandatory because current experience indicates that there is not a problem with the use of pallet racks at low temperatures in Europe.

Statistical treatment of test results

The European code requires a minimum of three identical tests to be made for every test configuration and that the characteristic values be derived using a consistent statistical approach.

The code details the requirements to be met by the testing establishment, demanding competent personnel, appropriate equipment and suitable levels of accuracy of measuring equipment. It draws attention to the need to create the correct test conditions, to ensure that loading methods are appropriate and take account of the likely deformation of the test sample, which must be prepared in an appropriate manner. There is a requirement for a fully detailed test report.

The purpose of testing is to provide characteristic values of strength, stiffness, looseness etc. for use in design. Manufacturers normally quote performance in terms of nominal dimensions and material properties. In general, it is not possible to arrange that test samples are endowed with these nominal properties and so adjustments must be made to the raw test data for variations in geometry and material specification. This is sometimes difficult to achieve in a rational fashion, especially when two different materials are present in a failure region and failure occurs in only one of them. In such a case, there is no information about the influence of the material which has not failed and the best that can be done is to check that the specification of this material is not too far from the nominal.

In order to calculate the characteristic values for strength, the 95% fractile with a confidence level of 75% has been adopted as the standard, and the relationship is:

$$R_k = R_m - k_s s$$

in which $\quad R_k$ = characteristic value
R_m = mean value of the test results
s = standard deviation of the test results
k_s = coefficient dependent on the number of test results

As a general rule, the standard deviation falls as the number of test results increases, The value of k_s ranges from 3.15 for three tests to 1.64 in the limit with many tests. In practical

terms, the consequence of this is that the more tests that are made to determine a particular value, the more favourable that value will be. Thus, investment in testing is rewarded by improved performance.

In the case of parameters such as stiffness and looseness, the average value of the test data is taken as the characteristic value to be used in design. In part, this is because connector stiffness, although an important property in determining the behaviour of a rack, is not directly related to failure. Stiffness is also an inherently more difficult parameter to measure than is strength. It normally relies for its determination on the measurement of both load and deflection and each of these is subject to error which tends to be cumulative in the derivation of stiffness. The use of the 95% fractile to calculate the characteristic values would be likely to give unreasonably low results.

Where a sequence of tests are made on a range of components or assemblies which are similar and in which one or more parameters are varied, the whole group of tests may be considered together in deriving the characteristic behaviour. This is possible provided that a suitable design expression can be written which relates the test results and all of the parameters varied during the test sequence. A polynomial obtained by a regression analysis is an example. The test results are first normalised by dividing each one by the corresponding value predicted the design expression, R_d, and the standard deviation, s, of the normalised values is then calculated using the whole population. The characteristic value for any set of values of the parameters is given by

$$R_k = R_d (1 - k_s s)$$

The advantage of this approach is that the standard deviation is based on a larger number of tests than could the case if each group of identical tests had been treated separately. The disadvantage is that a suitable design expression must be found. If the design expression does not accurately model the observed behaviour, the standard deviation may still be large.

Design of perforated columns

The design of the columns in pallet racks poses special problems. These members are generally of open cross-section and carry bending moments about both axes as well as significant axial load. There are, of course, well-developed procedures in Eurocode 3 [4] to deal with this case although it should be appreciated that the boundary conditions in the upright frames are not as clearly defined as in most conventional structures. However, the main problem concerns the regular arrays of perforations that are generally incorporated during manufacture in order to allow beams to be clipped into position at levels that do not need to be pre-determined.

Until very recently, it was considered that the only way to deal with this situation was to derive a column curve experimentally and procedures are described in the code whereby this may be done. Rhodes and Macdonald [7] have recently described tests on compression members containing regular arrays of perforations and have shown how these can be taken into account in design. In the context of the European design code, Leach and Taylor [8] have extended this approach and calibrated it against a comprehensive series of test results on racking uprights. In consequence, it is now considered to be possible to use stub column tests as a basis for a theoretical derivation of the column design curve. It should be noted, however, that it is also considered to be necessary to carry out a separate check in order to

ensure that distortional buckling is not significant. If it is, a procedure is given whereby the column curve may be de-rated to take account of distortional buckling.

The procedure that will generally, be used in the design of columns is firstly to carry out a set of stub column tests and then to make a separate check for the effects of distortional buckling. The approach is illustrated by reference to Table 4 which shows the results of a set of three stub column tests. The observed failure loads have been adjusted to correspond to a nominal thickness of 2.5 mm and a design stress of 250 N/mm².

Test No.	Failure load kN	Thickness mm	Yield stress N/mm²	Adjusted failure load kN
1	123	2.53	285	107.8
2	125	2.56	283	106.6
3	120	2.54	282	104.7
			Average R_m =	106.4
			Std. deviation s =	1.56
			Characteristic R_k =	101.5

Table 4   Results of stub column tests

In the table, the characteristic value of the stub column load has been calculated as the 95% fractile with a confidence level of 75% using $k_s = 3.15$. Thus the initial value of the nominal stub column strength is:

$$A_{eff}f_y = 101.5 \text{ kN}$$

In which A_{eff} =   effective area of the perforated cross section
               f_y =   design stress

A set of compression tests are then made on columns 800 mm long corresponding to the smallest bracing gate for this particular system. These failed in a torsional flexural mode and the test results are shown in Table 5.

Test No.	Failure load kN	Thickness mm	Yield stress N/mm²	Adjusted failure load kN
1	108	2.51	283	98.5
2	103	2.55	273	92.5
3	101	2.53	280	91.4
			Average =	94.1

Table 5   Results of compression tests on columns

Again the raw test results have been adjusted back to the nominal values for thickness and design strength. In the case of the latter, the adjustment is dependent on the slenderness ratio corresponding to the observed mode of failure.

The calculated failure load for torsional flexural buckling of the upright was,

$$N_{b,Rd} = 97.6 \text{ kN}$$

Which is greater than the average value obtained from the test series, indicating that distortional buckling may have a minor influence. Consequently, the characteristic value of the stub column load is modified so that the final value is,

$$A_{eff}f_y = 101.5 \times 94.1/97.6 = 97.9 \text{ kN}$$

This value is then used as the basis for the calculation of all design strengths for the upright in compression. As an example, using this reduced value of the stub column strength, the calculated value of the torsional flexural buckling load for the column whose test results are shown in Table 5 is 90.5 kN compared with the observed average value of 94.1 kN.

Semi-rigid joints

The design of a pallet rack or shelving system is usually dominated by consideration of the rather flexible clipped joints that are widely used in European practice. The performance of these connections has to be determined by test and consideration is given to separate consideration of the initial looseness as well as the stiffness. Markazi et al [9] have given detailed consideration to a number of proprietary connection systems and discussed the parameters and configurations that give rise to efficient beam and connector designs. Godley [10] has discussed the influence of connector stiffness on beam design.

The European design code allows two alternative test procedures to be used. These are illustrated in Figures 2 and 3. For the cantilever test in Figure 2, the measurement of moment and rotation are given by:

$$M = aF$$

$$\theta = \frac{\Delta_1 - \Delta_2}{d}$$

where a = lever arm for the load F
          d = distance between the gauges C_1 and C_2
         Δ_1 = deflection measured by gauge C_1
         Δ_2 = deflection measured by gauge C_2

For the portal frame test shown in Figure 3, the average moment in each connector is given by:

$$M = \left(\frac{Fh}{4} + \frac{W\Delta}{2}\right)\left(1 - \frac{d}{L}\right)$$

where d = width of the face of the upright
        Δ = $(\Delta_1 + \Delta_2)/2$

and the rotation of the connector is:

$$\theta = \frac{\Delta}{h} - F\left(\frac{h^2}{12\,E\,I_c} + \frac{h\,L}{24\,E\,I_b}\right)$$

where EI_c = flexural rigidity of the upright
EI_b = flexural rigidity of the beam

The calculation of the average moment in the connector and its rotation assumes that all of the components except the connector itself behave in a linear elastic fashion.

The design moment for the connection, M_{Rd}, is derived from the characteristic moment M_k by the relationship:

$$M_{Rd} = \frac{M_k}{\gamma_M}$$

where γ_M is the partial safety factor for connections.

M_{Rd} may take any value below the maximum allowed in order to optimise the stiffness of the connection when a bilinear characteristic is adopted in the design.

A typical moment rotation curve is shown in Figure 5 with a bilinear characteristic superimposed upon it. The connector stiffness is defined as the slope of the line which causes the connector to do equal work whether the actual curve or the bilinear model is followed to failure. It can be seen from this figure that, if the design moment M_{Rd} is reduced below the maximum value which is shown on the curve, the stiffness of the connector will increase.
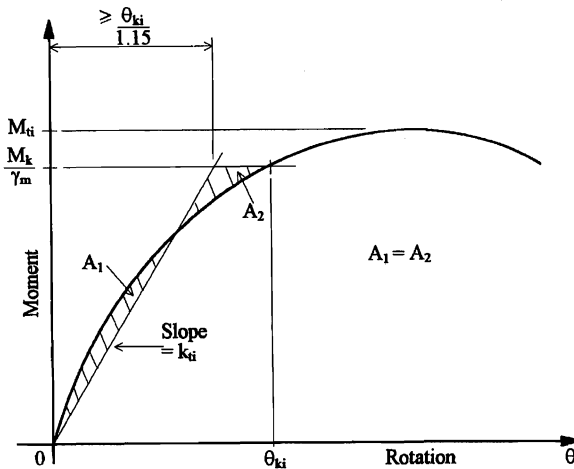
Fig. 5 Typical moment rotation characteristic for a connector with a bilinear model

Some connectors exhibit a highly non-linear characteristic. In such cases, the rotation at failure defined by the curve may be much higher than that implied by the bilinear substitute.

In order to avoid this situation, the rotation at failure assumed in the bilinear model may not be more than 15% less than that indicated by the test curve. The moment rotation curves for all the tests on a connector are analysed in this way and the average value of the stiffness is taken to be the design value.

Where the analysis method allows the use of a multi-linear model for the connector, the design moment for the connector is calculated in the same way. Then an average curve for the connector is calculated from all of the test results by plotting the mean value of the rotation at increasing values of the bending moment up to the design moment. The multi-linear model is defined as series of secant lines drawn below the average moment rotation curve.

In the case of the cantilever test, looseness is measured separately. The effects of looseness may be taken into account either by increasing the frame imperfections by an additional sway component or by adding the looseness as a horizontal or near horizontal line at the origin of the moment rotation model. In the case of the portal frame test, any looseness cannot be separately identified. It is incorporated into the moment rotation curve measured in the test which may, as a result, be more irregular than that obtained from the cantilever test and exhibit a lower stiffness.

Use of cold-reduced steel

A number of European manufacturers cold reduce their coil material before cold-forming it into racking components. This, of course, has the effect of raising the yield stress and reducing the ductility. It is well-known that reduced ductility is of particular concern in connections and this may be expected to be particularly the case with the clipped connections discussed above. To this end, tests on both components and complete installations have been carried out which have compared the performance of components cold-rolled from conventional and cold-reduced coil. Some of this work has been reported by Davies and Cowen [11]. It was concluded that the cold-reducing process had no adverse effect on performance.

Comparison of the European (FEM) and American (RMI) codes

Even allowing for the fact that, for member design, the RMI specification merely appeals to the AISI code whereas the FEM specification quotes the relevant clauses of Eurocode 3; Part 1.3 in full, the FEM code is the more detailed and more prescriptive. The FEM code describes global analysis in some detail whereas, in RMI, AISI procedures are merely implied. FEM has more load cases and considerably more onerous testing requirements.

The RMI Specification includes comprehensive seismic clauses in section 2.7. These are still under preparation in the FEM code.

At this stage, a comparison of the economic outcomes of using the two codes is not possible. The RMI code uses higher factors of safety and certain of the imperfection forces are also higher. However, this may be offset by such considerations as the inclusion of placement loads, the more rigorous treatment of sway stability and the statistical treatment of test results in the FEM code. The only way to resolve this would be by benchmark comparisons between the two codes and the worked examples in the codes offer a clear opportunity in this respect.

However, this work has yet to be carried out.

The two codes are both compared in more detail in the following sections:

Load factors etc

Both codes neglect the self-weight of the rack itself. The relevant load and material factors for the ultimate limit state are:

	RMI clause 2.2		FEM clauses 2.7.3 & 2.7.4
Dead	1.2	Dead	1.3
Live	1.6 (not pallets)	Live	1.5 (not pallets)
Pallets	1.4	Pallets	1.4 (1.3 if weighed)
Snow/Rain	0.5		

γ_m for columns $\quad$ 1/0.85 $\qquad\qquad$ γ_m for columns $\quad$ 1.1
γ_m for beams $\quad\;$ 1/0.9 $\qquad\qquad\quad$ γ_m for beams $\quad\;\;$ 1.0

Combined load factors:

for columns: 1.4/0.85 = 1.65 $\qquad$ for columns: 1.4/0.9 = 1.56
for beams: $\;\;\;$1.4/0.9 $\;\,$= 1.56 $\qquad$ for beams: $\;\;\;$1.4/1.0 = 1.40

Note see also FEM clause 2.7.1 for combination factors

Imperfection loads

Maximum tolerance from vertical: $\quad$ RMI cl 1.4.11 $\qquad$ FEM cl 1.13.1
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad$ 1/240 $\qquad\qquad\qquad$ 1/350

Horizontal imperfection force: $\qquad$ RMI cl 2.5.1 $\qquad$ FEM cl 2.5.1
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad$ 1½% of factored $\quad$ Variable depending on out-plumb
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad$ dead + pallet load $\;$ and connector looseness.
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad$ Typically about ½% of the factored
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad$ pallet load.

FEM is significantly less onerous here

Placement loads

Placement loads have a significant effect on FEM design. There are no placement loads in the RMI code.

Beam deflection (vertical - in the service condition, excluding impact)

$\qquad\qquad\qquad\qquad\qquad\qquad$ RMI clause 5.3 $\qquad\qquad$ FEM clause 2.3.4
$\qquad\qquad\qquad\qquad\qquad\qquad$ L/180 $\qquad\qquad\qquad\qquad$ L/200

Sway deflection   AISI - not considered   FEM clause 4.2.3
                                                                    h/200 at the top of the rack

Pattern loading

RMI - Not in the specification but used in   FEM - Specified in clause 4.2.2.1
practice in a similar way to FEM.   (Fig 4.1)

Member design

There are major differences in the presentation of the two codes though, with two possible
exceptions (cross-aisle bending and distortional buckling), it is likely that they lead to similar
outcomes. RMI merely appeals to the AISI code and includes, for both axially loaded
columns and bending elements, a modification for the effect of perforations. FEM quotes the
relevant sections of Eurocode 3, Part 1.3. It includes a treatment for perforations in axially
loaded columns but the bending behaviour of perforated elements requires testing. Both codes
combine the axial load and bending behaviour of uprights in an interaction equation.

Significant differences in member design procedures

RMI	FEM
No cross-aisle bending.	Cross-aisle bending arises primarily from the horizontal placement load. This also requires the determination (test) of the cross-aisle bending capacity.
Axial capacity by stub column test.	Axial capacity by stub-column test
But milled ends and fixed loading platens.	But either milled ends and fixed loading plattens or pinned ends and variable loading position. Consideration of neutral axis shift in the Eurocode is removed from the FEM code.
No consideration of distortional buckling.	Consideration of distortional buckling.
Approximate Q-factor for down-aisle bending.	Down-aisle bending capacity determined by test.
Implied (AISI) enhancement of bending moments due to second-order effects together with effective length factor K=1.7 for unbraced racks (K=1.0 for braced racks)	Specified enhancement of bending moments due to second-order effects together with effective length factor K=1.0.

Global Analysis

In the RMI Specification, the global analysis requirements are implicit by appeal to AISI. In FEM, they are specific. With one exception, the end results should be similar. The exception arises from <u>frame classification</u> (clause 4.3.3.1) in FEM.

RMI allows "average" pallet loads for sidesway stability analysis.

<u>Note</u> The side-load requirements for global analysis are quite different between the two codes.

Moment-Rotation Characteristics

This is, of course, a crucial aspect of pallet rack design and there are significant differences between the two approaches.

<u>RMI</u>	<u>FEM</u>
Uses cantilever test for moment capacity and portal test (cl 9.4.2) for M/θ relationship.	Uses cantilever test for <u>both</u> moment capacity and M/θ relationship <u>or alternatively</u> the portal test for both.
No separate consideration of "looseness"	Separate consideration of looseness which may be included in <u>either</u> the sway imperfection <u>or</u> in the M/θ relationship.
Statistical interpretation optional and on a quite different basis to FEM.	Formal statistical interpretation of test results is required.

Other aspects of testing

FEM includes the following mandatory tests which are not part of the RMI requirements:-

<u>Connector looseness test</u>   clause 5.6

<u>Shear test on beam end connector</u>   clause 5.7

<u>Shear stiffness of upright frames</u>   clause 5.9

<u>Bending test on upright sections</u>   clause 5.10

<u>Bending test on beams</u>   clause 5.11   <u>Note</u> twist limitation

<u>Tests on upright splices</u>   clause 5.15

The following test is included in FEM and may be of interest:

<u>Floor connection.</u>

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Conclusions

European harmonisation of design procedures for pallet racking has been a long process and has not been easy. However, it has been possible to harmonise long-held and disparate national procedures and traditions and the authors commend the resulting code as representing European-wide consensus of the current state-of-the-art.

A world code for the design of pallet racking is a realistic possibility. The authors hope that this paper may be a helpful step towards this end.

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