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The Behaviour of Drive-In Storage Structures

M H R Godley[1]

Abstract

The paper describes the behaviour of Drive-in and Drive-thru pallet rack structures. It proposes a number of simplified two-dimensional models for the analysis of such structures. These models are shown to be conservative and take account of the non-linear behaviour of the structures. The paper makes some comparisons between the output from these and a 3-D finite element program. The effects of friction between the pallet and the supporting rail is discussed briefly.

Introduction

This paper is about Drive-in and Drive-thru storage structures and their analysis and design. Both Drive-in and Drive-thru racks are structures that allow very high storage space utilisation at the price of reduced accessibility compared with conventional pallet racks. For normal pallet racks there are a number of design standards available in Europe[1,2], the USA[3] and Australia[4] but for Drive-in and drive-thru racks the SEMA[2] standard is the only one in common use and has not changed significantly for many years.

A Drive-in rack is shown in figure 1 in front and side elevations and in plan. Stability in the left-to-right direction is provided by the flexural stiffness of the portal beams and by the spine bracing at the rear. This is linked to forward parts of the rack by plan bracing over the top.

The rack shown is 5 pallets deep, three pallets high and may have many bays. The pallets are stored on pallet rails by fork-lift trucks which enter the rack from the front (or the rear in some lanes) to deposit or collect a pallet. Access to any particular pallet is restricted by the presence of other pallets on the same rails and by those on rails above and below it.

For this reason this type of racking is usually used for the bulk storage of goods all of the same kind where accessibility to a particular pallet is not a high priority.

Drive-thru racks are similar to Drive-in racks but have no spine bracing. This has the operational benefit that access to the rack is the same from the front and the rear in all lanes. Now, however, the left-to-right stability is provided by portal frame action alone.

In the front-to-back direction both types of rack are braced. In the example shown, pallet racking frame bracing is used to link adjacent columns and the pallet rails tie the frames together.

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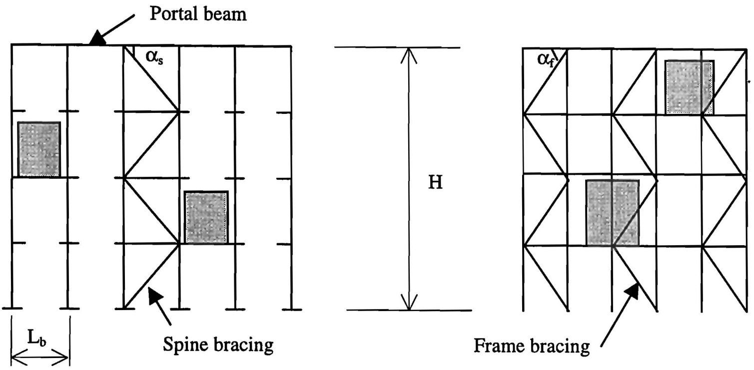
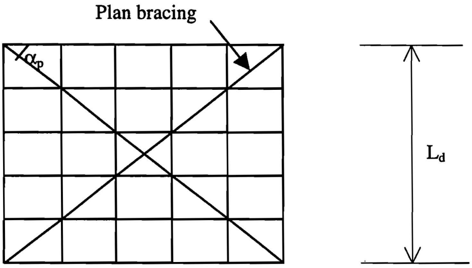


Front Elevation

Side elevation



Plan

Figure 1. Typical Drive-in structure

Analysis of these racks is straightforward if a three dimensional package is used, but this is a rather cumbersome approach when accurate information about the load carrying capacity of any configuration is required at short notice for the purpose of costing and estimating. In this paper some alternative approaches to the analysis of such racks are presented which are efficient and accurate.

Loading

The primary loading on the rack comprises the weight of the pallets combined with the effects of frame imperfections. The latter may be modelled either by setting the columns out-of-plumb or by applying an equivalent horizontal load. In addition to this, account should be taken of the minor impacts that occur during placement of the load, and of course member imperfections.

The pallets are supported on the pallet rails, eccentric to the columns. In the fully laden rack this means that the internal columns are centrally loaded and only the two lines of columns at the ends of the rack are subjected to offset loading. These end columns carry only 50% of the vertical load, however and are not usually critical.

When a pallet is absent in any aisle, the internal column adjacent to the empty space is subject to eccentric loading and hence local bending, combined with reduced vertical loading, and may be critical.

The effects of part loading, that is the effect of a single pallet being absent from an otherwise fully loaded rack, and placement are not included in what follows. Part loading is a local effect that does not have a sway component and may be dealt with by superposition. Placement loading may be dealt with either as a local effect or by the application of an additional distributed side load.

Drive-thru racks

The failure mode for Drive-thru racks is a sway failure from left-to-right as shown in figure 2. The elastic buckling load is dependent upon the stiffness of the portal beam and its connection to the column. This connection is often a semi-rigid pallet rack connection comprised of hooks which engage in slots in the front of the column. The base of the column is usually bolted to the ground and is very stiff, so that it behaves as a fixed base. The FEM[1] code describes test methods for determining the stiffness of such bases in cases of doubt.

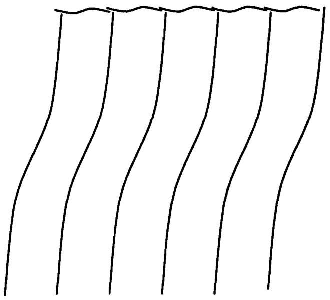


Figure 2. Sway failure mode for a Drive-thru rack

The construction of a Drive-thru rack is regular and it may be analysed by considering a single column, loaded at each level and restrained by rotational springs at the top and bottom. Figure 3 shows such a single column in isolation, fully loaded at each level. At the base it is fixed and at

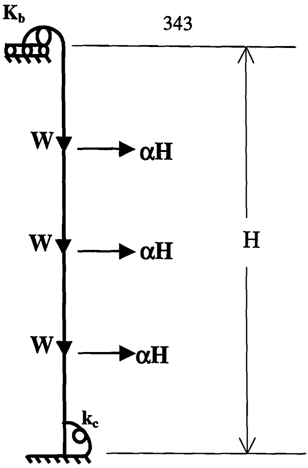


Figure 3. Single column model for a Drive–in rack

the top the restraining effects of the beam and its connector are represented by a rotational spring.

In the sway mode the portal beam is put into double curvature which is anti-symmetric for a rack with a significant number of bays, so that the spring stiffness is given by,

$$K_b = \frac{2k_b}{(1 + \frac{k_b L_b}{6EI_b})}$$

in which,

k_b = stiffness of the beam end connector

EI_b = flexural rigidity of the portal beam

L_b = span of the portal beam

The slenderness of such racks is usually quite high and consequently a second order analysis is recommended. This may be carried out on the single column and the normal interaction design checks made to ensure structural adequacy. The use of a single column is conservative because the stiffening effect of the part-loaded end columns are neglected. This may be accounted for by enhancing the flexural properties of the columns.

When a second order analysis is made the effect of member imperfections may be included in the global analysis. Alternatively they may be included by using a column curve. In that event the system length, H, could be used to determine the compressive strength, but when a buckling analysis shows that the actual buckling length for the column is less than the system length, the true buckling length may be used.

The SEMA[2] code recommends that for fully loaded columns of the type shown in figure 3 the effective length may be taken as 0.75H provided the centre of mass of the payload is at less than 2/3H, where H is the height of the rack. This is then used in a linear analysis to design the column.

To show the significance of the stiffness of the portal beam, the model in figure 3 has been analysed with the axial load equally shared on 10 levels. Full fixity has been assumed at the base. In terms of the non-dimensional stiffness, K_bH/EI_c the variation of the non-dimensional total buckling load $p_{crit}=P_{crit}\,H^2/EI_c$ is plotted in figure 4. In these expressions EI_c is the flexural rigidity of the column.

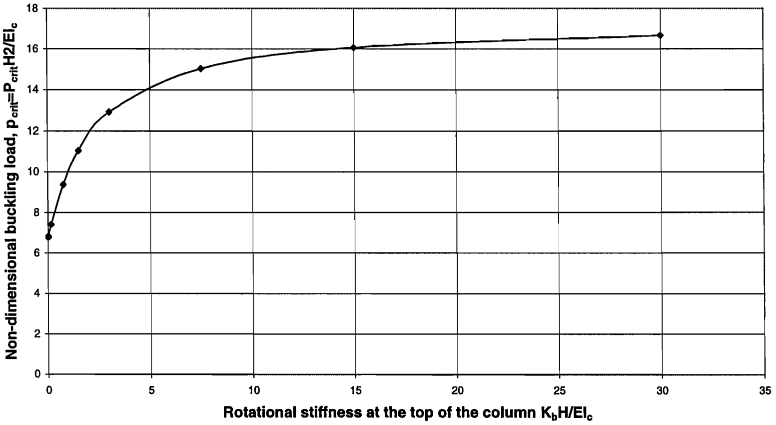


Figure 4. Variation of elastic buckling with rotational stiffness at the top

As expected the elastic buckling load increases as the rotational stiffness increases. The range of values of p_{crit} is from 6.84 when the top is pinned to about 17 when both ends are fixed. For the pinned case Timoshenko[5] provides a solution, $p_{crit}= 6.48$ for a uniformly distributed axial load. From the same curve it can be seen that for values of the spring stiffness above 10, the elastic buckling load is still more than 90% of the full fixed end value. For efficient use of the section the top stiffness should be as large as possible.

It may be noted that the effective length of such a column does not reduce to 0.75H until the non-dimensional stiffness is about 30. This requires quite a high stiffness for the portal beam assembly and it may not always be reached.

For a typical Drive-thru rack with the proportions shown in figure 1(but with no spine bracing) 7.2m high, a buckling analysis using the single column model gives an effective length factor for the column of 0.94. Using this length to determine the compressive strength of the column, based on a typical set of section properties, the payload per level is 5.31kN. This will provide a basis for comparison with a Drive-in rack of the same proportions. A 3-dimensional analysis by finite elements gave an effective length for the column of 0.81.

Drive-in racks.

Models for analysis

For a Drive-in rack, the spine bracing provides some horizontal restraint at the top so that sway is restricted. The stiffness of this restraint is an important factor in determining the elastic buckling load factor for the rack.

Several alternative models may be adopted to simplify and speed the design of a Drive-in rack. The simplest is a single column model of the type shown in figure 5. This is the same as the Drive-thru single column model but has an additional horizontal spring at the top of the column to represent the restraining effect of the bracing system. Care must be taken to obtain an accurate estimate of the spring stiffness. This stiffness is dependent upon the linked stiffnesses of the plan, spine and frame bracing in the structure.

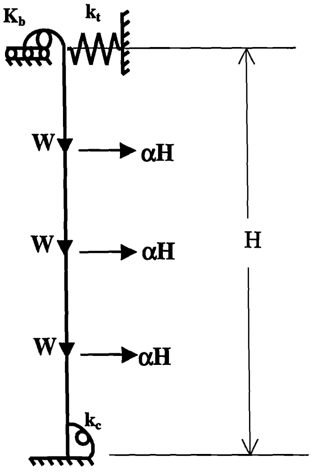


Figure 5. Single column model for a Drive-in rack

An alternative approach is to unfold the bracing system to make a plane frame structure which has all the essential features of the original 3-dimensional frame.

Unfolded rack

The rack is unfolded in the manner shown in figure 6. Here the plan bracing is rotated upwards about the axis of the rearmost portal beam and rigid ties link from the plan bracing to the tops of the appropriate columns. The front face of the rack now appears at the top of the diagram

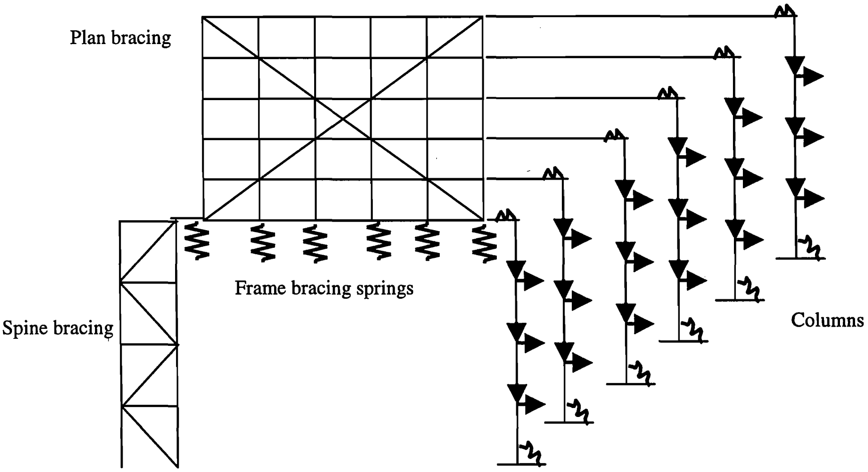


Figure 6. Arrangement for the unfolded rack

The plan bracing is prevented from rotating about the vertical axis as a rigid body by the resistance of the lines of braced columns running from front to rear of the rack. This resistance is modelled by a linear spring at each node of the plan bracing grid. (only one line of these is shown in figure 6 for the sake of clarity)

The flexural properties of the columns are the aggregated properties of all the columns in that line. The loads and the stiffnesses are also aggregated. This model is now a plane frame on which a second order analysis can be made.

After a second order analysis of the rack, an inspection of the column members shows that the first fully loaded column in each lane nearest the front of the rack is usually critical. The columns on the front face of the rack perceive the lowest horizontal bracing stiffness, but they carry only half the vertical load of the internal columns. The first column in from the face of the rack is fully loaded and it sees the lowest stiffness from the bracing system of all those in its lane.

Using the same set of section properties and loads as for the Drive-thru rack, the elastic buckling load factor for the unfolded rack is 2.08. This is the same as that obtained from a buckling analysis of the three dimensional rack using a finite program. It corresponds to an effective length factor of 0.46. In the SEMA[2] code of practice the recommendation is for an effective length factor of 0.75 for a structure of this type.

When this buckling length is used to determine the compressive strength of the columns, the payload per column per level becomes 15.0kN, nearly three times the payload for the unbraced Drive-thru rack.

Single column model

In any single column model of this structure, it is the apparent stiffness of the horizontal bracing system at the top of this column that must be calculated. The rotational stiffness of the portal beam is the same as for the Drive-thru column.

Under the action of horizontal loads such as those caused by frame imperfections, the columns tend to sway. This sway is resisted by the plan bracing which in turn is restrained from horizontal movement by the spine bracing. The plan bracing is prevented from rotating about the vertical axis by the resistance of the frame bracing to sway in the down-aisle direction.

Figure 7 shows the loading pattern to which the bracing system is subjected in a regular rack. The inner columns are all fully loaded while the peripheral columns carry 50% of the vertical load. Side loads are essentially proportional to the vertical loads, hence the pattern shown in figure 7 in which the load transmitted at the top of each fully loaded column is given by f. The number of columns in one row of one lane is N_u. The total shear applied to the plan bracing is $(N_u-1)^2f$. This load distribution appears to hold good at all stages of loading.

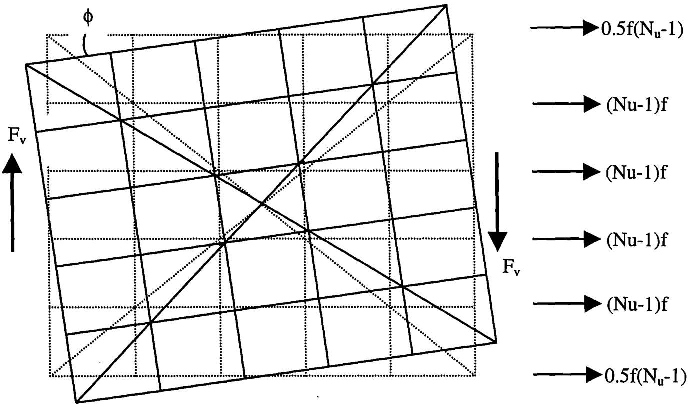


Figure 7. Horizontal loads on the bracing and body rotation of the plan bracing

The significance of the different components of the bracing system depends upon the geometry of the rack structure as well on the geometrical properties of the structural sections. The braced part of the rack behaves linearly and so the deflections of the different components may be computed by hand and explicit expressions can be derived for each of them.

The stiffness of the plan bracing system is usually relatively very large and can be calculated assuming that the flexibility of all but the diagonal members is negligible. The bracing system is assumed to behave linearly and members are all taken to be pin-jointed. Then, under the action of the set of loads in figure 7, the deflection of the front face of the rack due to distortion of the plan bracing is,

$$\Delta_p = \frac{fL_d(N_u - 1)^2}{4A_pE\sin\alpha_p\cos^2\alpha_p}$$

in which A_pE is the axial rigidity of the plan bracing diagonals, and α_p their angle of inclination. L_d is the depth of the rack from front to back.

In calculating the stiffness of the spine bracing system, the flexibility of the members which form part of the bracing system is significant when the aspect ratio (ratio of height to width) is more than unity, because then the bracing forces induced into the columns are significant. For this reason it is often desirable to link several spine braced bays together. The horizontal displacement of the top of the rack due to spine bracing distortion is given by,

$$\Delta_s = \frac{f(N_u - 1)^2 H}{E}\left\{\frac{1}{A_s\sin\alpha_s\cos^2\alpha_s} + \frac{\tan^2\alpha_s(2(N_s^2 + 1) + 1)}{3A_c}\right\}$$

The plan bracing is supported by the tops of the columns and under side load, tends to rotate in the manner shown in figure 7. Shear forces are applied in the front to back direction to the tops of the braced frames. The resistance to this rotational movement is provided primarily by the two rows of columns at the ends of the plan braced panels.

In these rows there are frame braced panels and if these are fabricated from standard pallet racking components the bracing connections may be quite flexible, reducing the effectiveness of the bracing system to as little as 15% of the full theoretical value. For this reason a shear test of the kind set out in the FEM[1] code of practice may be advisable to measure the stiffness of these panels. The flexibility of the columns is relatively insignificant.

The deflection at the top of a row of frames, under the action of a force F_v, is given by,

$$\Delta_f = \frac{2F_vH}{N_uA_fE\sin\alpha_f\cos^2\alpha_f}$$

and this imparts a rotation to the plan bracing, ϕ, given by,

$$\phi = \frac{2\Delta_f}{(N_u - 1)L_b}$$

Due to the action of the set of horizontal forces shown in figure 7,

$$F_v = \frac{f(N_u - 1)L_d}{2L_b}$$

and the deflection at the front face of the rack is,

$$\Delta_\phi = \phi L_d$$

which may be written as,

$$\Delta_\phi = \frac{2fHL_d^2}{N_u L_b^2 A_f E \sin\alpha_f \cos^2\alpha_f}$$

The critical column is not usually the front face column which carries only a 50% load, but the column immediately behind it which is fully loaded. For this line of columns the horizontal deflection at the top is given by,

$$\Delta = \Delta_s + (\Delta_p + \Delta_\phi)\frac{(N_u - 1)}{(N_u - 2)}$$

and for one column the horizontal stiffness, k_t, at the top is,

$$k_t = \frac{f}{\Delta}$$

In the example shown in figures 1 and 6 there are only 5 bays and six columns in each bay. In plan the aspect ratio is nearly square. In many such installations there are many bays and the shape is rectangular with the long side parallel to the front face of the rack. In such cases the significance of the plan bracing rotation diminishes and it is only necessary to provide an adequate number of spine braced bays.

A typical set of section properties and dimensions were used in the example shown in figure 6 and the stiffness calculated, so that,

$$k_t = 0.0177\,\text{kN/mm}$$

This compares with the figure of 0.0202kN/m measured from an analysis of the model in figure 6. Hence the single column model is conservative.

Using this stiffness in the single column model shown in figure 5 the elastic buckling load factor is found to be 1.85, about 10% lower than the unfolded model. A check on the columns in the same manner as before gives a payload of 14.2 kN per column per level, some 5% lower.

Other design considerations.

So far this paper has considered only the behaviour of a typical fully loaded column. Other important design considerations are the strength of the semi-rigid connection at the column base and at the portal. In addition, consideration must be given to the strength of the bracing members and to the effect of loads induced into the columns by the action of the bracing systems. This is especially true of the columns that form part of the spine bracing system which may be subjected to significant overturning forces. Uplift of the column on the leeward side of the spine bracing can be a major problem in a part loaded rack.

In the service condition, consideration must be given to sway deflections and also to the potential for flexure of the columns to allow a pallet to fall between the rails if the tolerances are incorrectly chosen. Some recommendations for this situation are contained in the FEM[6] specifiers' guide.

Pallet friction has played no part in the foregoing calculations. The coefficient of friction between timber and steel is quoted in BS 5975[6] as 0.2 and in DIN 4421[7] as 0.5. These figures are used in the falsework industry where surface finishes may be a little different from those used in racking systems. However they indicate that frictional resistance is substantial. Even with a coefficient of 0.2, frictional forces at 20% of the vertical loads are large in comparison to the side loads that are used in the design of a Drive-in rack.

Any fully loaded pallet in position on the pallet rails effectively introduces its own set of plan bracing at that level. Provided all the pallets are in place between that pallet and the rear of the rack so that this plan bracing links up with the spine bracing, there will be a substantial stabilising effect to the columns. However, if not all the pallets are in place, the bracing effect remains local one and makes little contribution to the overall stability of the rack structure. To benefit from this effect would require very close management of the stored goods and this is not normally practicable or desirable.

Conclusion

This paper has discussed methods of design and analysis for Drive-in and Drive-thru racks. Alternative methods of analysing both types of rack, avoiding the use of a large general purpose analysis program are proposed. For Drive-thru racks a simple single column model is shown to be adequate for regular configurations while for Drive-in racks a two dimensional unfolded model is offered in addition to the single column model.

Appendix – References

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8. Deutsche Institut fur Normung. DIN 4421, Falsework, Calculation, design and construction. 1982.

Appendix - Notation

A_c	Cross-sectional area of column
A_f	Cross-sectional area of frame bracing diagonal
A_p	Cross-sectional area of plan bracing diagonal
A_s	Cross-sectional area of spine bracing diagonal
A_f	Cross-sectional area of frame bracing diagonal
α	frame imperfection angle
α_f	angle of inclination of frame bracing diagonal
α_p	angle of inclination of plan bracing diagonal
α_s	angle of inclination of spine bracing diagonal
Δ	horizontal displacement of the penultimate column
Δ_ϕ	horizontal displacement due to rigid body rotation of the plan bracing
Δ_f	horizontal displacement of the frame bracing
Δ_p	horizontal displacement of the plan bracing
Δ_s	horizontal displacement of the spine bracing
E	elastic modulus
ϕ	rigid body rotation of the plan bracing
f	horizontal reaction at the top of a fully laden column
F_v	horizontal load on the frame bracing
H	rack height
I_b	second moment of area of the portal beam
I_b	second moment of area of the column
k_b	rotational stiffness of the beam end connector
k_t	horizontal stiffness at the top of the penultimate column
K_b	effective stiffness of the portal beam
L_b	bay width
L_d	rack depth
N_s	number of pallet levels
N_u	number of columns per lane
P_{crit}	elastic buckling load of one column

$$p_{crit} = \frac{P_{crit} H^2}{EI_c}$$