Impact tests and parametric impact studies on drive-in steel storage racks

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Abstract:

Extensively used in the industry to store goods, steel storage racks are frequently subjected to accidental impact forces from operating forklift trucks. There is currently little understanding of the nature of these impact forces, leading to occasional catastrophic failures because of inadequate structural design. International racking design codes deal with impact but use an arbitrary value of impact force with no scientific justification. This paper focuses on an impact-sensitive type of storage rack, called “drive-in racks”. Contrary to classical “selective racks”, where pallets are stored on beams and where each single pallet is always accessible, “drive-in racks” allow the forklift truck to drive into the rack to store pallets on beam rails, one after each other, on the first-in, last-out principle. This type of design leads to slender uprights in the down-aisle direction, only restrained at the base and at the top. When subjected to an impact force, the bowing of the upright triggers progressive failure by allowing the pallets to drop through.

This paper presents experimental results obtained from tests on a complete full-size drive-in rack structure subjected to the impact of a forklift truck. Parametric impact studies using finite element analysis are also presented. Factors affecting the sensitivity of drive-in racking structures to impact are investigated and conclusions are drawn about the parameters most significantly influencing the progressive collapse of this type of rack under impact.

Keywords:

Steel storage rack, drive-in rack, impact force, impact sensitivity.

1 Introduction

Steel storage racks are extensively used worldwide in industry for storing goods, mainly on pallets. They are predominantly made from cold-formed steel profiles and are competitively designed as lightly as possible. Due to intensive use, storage racks are frequently subjected to accidental impact forces from operating forklift trucks. There is currently little understanding of the nature of these impact forces, leading to occasional catastrophic failures.

“Selective racks”, the most common type of rack, are only one pallet deep and separated by aisles, allowing each pallet to be always accessible. When storing the same goods or in space-limited and expensive places such as industrial freezers, a more economical solution to selective racks is to store the pallets on rail beams, one after the other, with no space between them. In this more compact type of rack called “drive-in racks”, the forklift truck drives into the rack to store the pallets on the first-in, last-out

principle as illustrated in Figure 1. Drive-in racks are typically 3 to 7 pallets deep and can be numerous bays wide. Other types of racks are available in the industry and are described in [1].

To allow the forklift truck passage, drive-in racks can only be braced at the back (spine bracing) and at the top (plan bracing) in the down-aisle direction. This type of design leads to slender uprights in the down-aisle direction, only restrained at the base by the base plate assembly and at the top by the portal beam. When subjected to an impact force, the bowing of the upright may trigger progressive failure by allowing the pallets to drop through as shown in Figure 2.

The main international racking design codes only deal with selective racks and do not mention drive-in racks. For selective racking systems, it is believed that the most severe damages are induced by an impact of the rear counterweight of the forklift truck between the floor and the first beam elevation; see the RMI [2] specification (Rack Manufacturers Institute) and the European Standard EN 15512 [3]. The RMI [2] only makes recommendations to “safeguards racks against the consequences of minor collisions” between the floor and the first beam elevation. For manually operated forklift trucks, the EN 15512 [3] uses an accidental impact force of 1.25 kN in the down aisle direction and of 2.5 kN in the cross-aisle direction but only between the floor and 0.4 metres in height. On the other hand, the Australian Standard AS 4084 [4] uses an impact force applied at the most unfavourable location equal to the maximum of the unit load/15 and 0.5 kN, in both cross-aisle and down-aisle directions, for manually operated forklift trucks. However, the above impact forces are arbitrary and have no scientific justification.

Figure 1: (a) Typical drive-in rack and (b) Forklift truck driving in the rack and placing pallet load

The Fédération Européenne de la Manutention is currently developing a code dealing specifically with drive-in racks (FEM 10.2.07 [5]). In the current draft state, this code considers horizontal impact loads as in the EN 15512 [3] standard for selective rack and manually operated forklift truck. However, impact at higher elevation than 0.4 metre is considered by means of placement loads. The FEM 10.2.07 [5] states that even through placement loads are not intended to represent accidental impact loads, it “may be assumed to include adequate allowance for ordinary impact conditions”. The horizontal

placement load is equal to 0.5 kN for both the cross-aisle and down-aisle directions and has to be applied at the most unfavourable beam rail elevation.

In the literature, very few investigations have been reported on storage racks under impact and they only concern selective racks with an impact at the bottom of an upright. To the authors' knowledge, impacts on drive-rack structures have not been yet reported. McConnel [6] investigated the collapse of selective racks when the bottom of an upright is lost due to a forklift truck impact. The paper focuses on the nature of the collapse (confined or progressive) but not on the impact itself: the impact was simply assumed to be strong enough to remove the lowest section of one of the rack uprights. Bajoria [7] improved McConnel [6] work using 3-dimensional analysis and experimental tests on complete storage racks. Yet the impact was still assumed strong enough to remove part of an upright. Ng [8] investigated the dynamic behaviour of selective racks during and after impact. The impact force at the bottom of a leg is calculated using the energy of the forklift truck during impact but is not based on actual testing. Impacts on various structures can be found in the literature but they mainly concern "bullet type" or "blast type" impacts, which correspond to an impact duration much less than the impact duration encountered during a forklift truck impact on drive-in rack structures.

Actual impact tests on a complete full scale drive-in rack structure have been performed in the down-aisle direction, in the Structures Laboratory of the School of Civil Engineering at the University of Sydney. The drive-in rack structure is 4 pallets deep, 4 bays wide and 4 stories high (i.e. featuring 3 beam rail levels) and designed to carry 2 tons per pallet. Further details of the tested drive-in rack are reported in [9]. In the studied configuration, the plan and spine bracings run over 1 bay. Six series of twenty tests each, representing three loads carried by the forklift truck and two rack loading configurations have been conducted by striking the rack with an actual forklift truck.

The rack was supplied by Dematic Pty Ltd and corresponds to a currently available commercial drive-in rack. It is designed to carry 2 tons pallet loads using the proprietary software RAD ([10]) developed in-house by Dematic Pty Ltd. RAD performs a 3D elastic second-order analysis, assumes a linear rotational stiffness for the base plates, and takes into account the warping torsion and shear-centre eccentricities of rack members. The rigidity in the horizontal plane afforded by the pallets is not considered in RAD. The loading conditions and load cases programmed in RAD are based on the AS 4084 [4], AS/NZS 1170.1 [11] and FEM 10.2.07 [5] standards, while the member and component design checks are based on AS/NZS 4600 [12].

This paper presents the experimental test set-up and results of the actual impact tests. Results from a Finite Element (FE) model of the drive-in rack under impact are also presented and are found to reproduce the experimental results with good agreement. Parametric impact studies using FE analysis are presented hereafter and factors affecting the sensitivity of drive-in racking structures to impact are investigated. Finally, conclusions are drawn about the parameters most significantly influencing the progressive collapse of this type of rack under impact.

Figure 2: Bowing of upright and failure due to pallet dropping through during forklift truck impact on a drive-in storage racking structure (Elevation – Front view)

2 Experimental test set-up

2.1 Impact cases

An impact by the rear counterweight of the forklift truck occurs on the lower part of the upright and will not bend the upright of a drive-in rack sufficiently to trigger the failure mode shown in Figure 2. For a pallet to drop through, the load has to be raised and it is the pallet carried by the forklift truck which impacts the rack as illustrated in Figure 2. Both impacts in the cross-aisle and down-aisle directions can occur but only impacts in the down-aisle direction will trigger failure as shown in Figure 2.

Under impact in the cross-aisle direction, the forklift truck driver misjudges the location of the truck and drives straight into the rack as illustrated in Figure 3 (b). Failure due to impact in the cross-aisle direction is likely to occur due to local structural damage of the upright which is then unable to maintain its design function. Indeed, the presence of the bracing members of the upright frames mainly allows the upright to absorb energy by local deformation rather than by global bending.

Figure 3: Forklift truck impact with the load raised on storage rack structures in (a) and (b) cross-aisle direction and (b), (d) and (e) down aisle direction

Under impact in the down-aisle direction, while placing or removing a pallet on the rack, the forklift truck driver misjudges the location of the truck and starts turning

before the pallet is cleared of the rack. The forklift truck, by typically rotating about its front wheel axis, causes the pallet to impact with the front upright of the rack, as shown in Figure 3 (d) and (e).

Experimental impact tests in the down-aisle direction have been carried out for the case where the forklift truck impacts the rack during the pallet removal as shown in Figure 3 (d). There is no reason to believe that an impact resulting from pallet placements as shown in Figure 3 (e), would give significantly different impact forces.

2.2 Experimental set-up

A plan view of the tested drive-in rack with associated gridlines is given in Figure 4. Each upright is referenced by the letter and number of the gridlines intersecting at its location. The four bays are referenced as bays AB, BC, CD and DE.

Figure 4: Tested drive-in rack gridlines

1.2 tons and 2 tons concrete blocks placed on wood pallets are used to load the rack and reproduce real operating conditions. During the forklift impact tests, two different rack loading configurations referred to as “Impact BC” and “Impact CD” have been investigated. For “Impact BC”, bays AB and DE are empty, bay CD is fully loaded and bay BC is partially loaded as detailed in Figure 5 (a) in Table 1. The forklift truck is positioned in front of bay BC and upright B1 is impacted at 150 mm above the second rail beam elevation. This configuration allows the impacted upright to deform freely by avoiding the horizontal bracing effect of adjoining pallets. For “Impact CD”, bays AB and DE are empty, bay BC is fully loaded and the two front pallets are removed in bay CD which is otherwise fully loaded as detailed Figure 5 (b) and in Table 2. The forklift truck is positioned in front of bay CD and upright C1 is impacted at 150 mm above the second rail beam elevation. This configuration investigates the horizontal bracing effect of adjoining pallets on the impacted upright deformation. The previous configurations may not represent the worst loading case in terms of member capacity but allow varying the stiffness of the rack at the impact point and investigating two different resistances to impact.

Figure 5: Loading configuration for (a) “Impact BC” and (b) “Impact CD”

Two Linear Variable Displacement Transducers (LVDTs) record displacements in the down-aisle direction of the impacted upright and of the directly opposite front upright as shown in Figure 6. The LVDTs are positioned at the shear centre line of the uprights at the impacted elevation. This configuration allows the measurement of the overall displacement d_o of the rack at the impact point (LVDT 52) and the total displacement $d_o + d_u$ of the impacted upright (LVDT 53). The upright bending displacement d_u (LVDT 53 - LVDT 52) represents the bay opening at the impact point, where the bay opening is defined as the difference in distance between two consecutive uprights in the down-aisle direction and reflects the possibility of a pallet to drop through.

In a first series of tests, the stiffness of the overall rack (k_o) and of the impacted upright (k_u) at the impact point in the down-aisle direction are investigated. A 250 kN capacity DARTEC servo-controlled hydraulic jack is connected at the shear centre line of the impacted upright at the impact elevation. The jack pulls statically on the rack in the down-aisle direction (see Figure 6) at a low displacement rate. Displacements d_o and d_u are recorded.

Figure 6: LVDT locations for (a) “Impact BC” and (b) “Impact CD” (Elevation – Front view)

In a second series of tests, actual impact tests are performed. Before each test the forklift truck is positioned in bay BC for “Impact BC” and in bay CD for “Impact CD” with its load raised to the impact elevation. The forklift truck then reverses while turning about its front wheel axis to impact the desired upright with the edge of its pallet. The forklift truck used is a NICHYU FB20, 2 tons load capacity. For each loading configuration, 60 tests are performed representing 3 series of 20 tests each with the forklift truck carrying a 300 kgs, a 775 kgs or a 1175 kgs weight on the pallet. The

increase in the load carried by the forklift is expected to increase the momentum of the forklift truck during impact.

3 Experimental results

3.1 Static test results

The overall static stiffness of the rack k_o at the impact point is defined as,

$$k_o = \frac{F}{d_o} = \frac{F}{d_{52}} \quad (1)$$

where F is the force applied by the hydraulic jack and d_{52} is the horizontal down-aisle displacement obtained from LVDT 52. The bending stiffness of the upright k_u is defined as,

$$k_u = \frac{F}{d_u} = \frac{F}{d_{53} - d_{52}} \quad (2)$$

where d_{53} is the reading of LVDT 53. Table 3 gives the initial stiffness values found for both loading configurations “Impact BC” and “Impact CD”. It is observed that whereas the values of k_o are similar for both loading configurations, the values of k_u for “Impact CD” configuration are significantly larger than for “Impact BC” configuration. This difference is mainly due to the horizontal bracing effect of pallets as mentioned in [9].

3.2 Impact test results

Figure 7 and Figure 8 plot LVDTs 52 and 53 displacements against time and the front bay opening d_u against time for tests 207 and 23 respectively. Test 207 represents an “Impact BC” configuration with a 1175 kgs load carried by the forklift truck and test 23 represents an “Impact CD” configuration with a 775 kgs load carried by the forklift truck. These tests represent typical and reproducible tests in terms of the rack behaviour, yet the amplitudes of LVDTs 52 and 53 vary between tests of a same series due to the forklift truck being manually and not automatically operated. The variation between tests is reported in [13] in terms of the motion of the body of the forklift truck.

Figure 7: Test 207 results - “Impact BC” configuration and 1175 kgs load on forklift truck: (a) LVDT 52 and 53, (b) bay opening or $d_u = \text{LVDT 53} - \text{LVDT 52}$

Figure 8: Test 23 results - “Impact CD” configuration and 775 kgs load on forklift truck: (a) LVDT 52 and 53, (b) bay opening or $d_u = \text{LVDT 53} - \text{LVDT 52}$

The test results show that an impact can be separated into four distinct phases. During the first phase, the overall rack essentially stays stationary while the impacted upright starts bending, opening the bay to its maximum value. In a second phase the overall rack starts its motion while the displacement at the impact point tends to reach a maximum, causing the bay opening to reduce. At one stage during the second phase, the pallet impacting the rack loses contact with the rack while d_{52} and d_{53} may still increase due to the inertia of the overall rack and the inertia of the impacted upright. In a third transition phase the impacted upright bends back to its neutral position. The rack is then free to oscillate during a fourth and last phase. Due to large amount of frictional damping between the pallets and the beam rails, the impacted upright does not oscillate and d_u is essentially equal to zero during the fourth phase.

One can deduct that if the bay opens widely enough to trigger failure, then failure is likely to happen during the critical first phase of the impact where the bay opening reaches its maximum. For “Impact CD” tests, the LVDT 53 reading of the upright bending and overall displacement ($d_u + d_o$) is closer to the LVDT 52 reading of the overall displacement (d_o) than for “Impact BC” tests. This may be explained by the greater stiffness k_u of the “Impact CD” test which reflects the horizontal bracing effect of the pallets adjoining the impacted upright D1.

4 Finite Element model results and model validation

4.1 General

The Abaqus [14] Finite Element model developed and detailed in [15] is used to analyse the dynamic response of the tested drive-in rack under forklift truck impact. The FE model is proved to accurately reproduce the static behaviour of the drive-in rack, see [15].

The model includes “elastic non-linear plastic” moment-rotation boundary conditions for the base plates. Typically, the base plate stiffness and strength depend on the axial load in the upright ([16], [17]) and this effect is considered in the FE model by allocating individual multi-linear curves to each base plate. The multi-linear curves are derived from the experimental test results described in [18]. Similarly, “elastic non-linear plastic” moment-rotation curves, which are based on the experimental test results described in [18], are used to model the portal beam to column connections.

Typically elements type B33 are used to model members, except for (i) uprights, which, to account for warping, are modelled using B32OS elements, and (ii) spine and plane diagonal bracing members which are modelled using T3D2 truss elements. Links are used to model interconnections between members to incorporate member eccentricities.

The base of the pallets is modelled using a grid of four cross-aisle beams and four down-aisle beams. When the rack is subjected to a horizontal force, the pallets undergo shear deformations and 44 mm diameter circular rods for the pallet base members are found to satisfactory reproduce the pallet shear stiffness ([15]). Using the “sliding angle method”, the kinetic friction coefficient between the wood pallets and the steel rail beams was experimentally found to be 0.3 and a “perfect stick-slide” nonlinear behaviour is considered at each point connecting the pallets to the rail beams. Additionally, for dynamic analysis, a structure using truss element type T3D2 is added on top of the base of the pallet to model the pallet mass at its centre of gravity; the arrangement of this structure does not add stiffness to the pallet. Figure 9 shows the FE model of the pallet.

Figure 9: Pallet FE model

For static analysis, a second-order geometric non-linear analysis is carried out, while for dynamic analysis better convergence was obtained using second-order geometric non-linear implicit analysis.

Damping for steel structures is small, typically between 0.1% and 0.9% (Bangash [19]), and hence the overall damping of the structure was ignored in the FE model. However the friction between the pallets and the rail beams generates nonlinear frictional damping for an upright bent away from its original position. This friction is significant and was modelled.

4.2 FE dynamic results using impact force as input

The accuracy of the FE model of the rack was first checked over the four phases of impact described in Section 3.2. Impact forces calculated using the simple mechanical models developed from 1st principles and detailed in the companion paper ([20]) are input in the global Abaqus model at the impact point location. These impact forces are time dependant and reproduce the actual force applied by the forklift truck on the rack. Figure 10 and Figure 11 compare Abaqus results for LVDT 52 and 53 against the experimental results of test 207 and test 23 respectively. Figure 10 shows excellent agreement between Abaqus and experimental results for the “Impact BC” configuration while Figure 11 shows reasonable agreement between Abaqus and experimental results

for the “Impact CD” configuration. The discrepancy shown in Figure 11 is believed to be largely a result of the complex nonlinear friction between pallets and beam rails.

In Figure 10 (b) and Figure 11 (b) it is observed that in the Abaqus model the friction effect between the pallets and the rail beams does not allow the upright to bend back to its neutral position leaving the bay slightly open after impact.

Figure 10: Test 207 results - Dynamic Abaqus FE results and impact experimental results for “Impact BC” configuration, (a) LVDT 52 and 53, (b) bay opening or d_u

Figure 11: Test 23 results - Dynamic Abaqus FE results and impact experimental results for “Impact CD” configuration, (a) LVDT 52 and 53, (b) bay opening or d_u

4.3 FE dynamic results using forklift truck

As detailed in the companion paper [20], the rotational motion of the forklift truck body is a common characteristic to all impact tests and can be calculated using the experimental test results combined with a simple mechanical model of the forklift truck. By modelling the forklift truck and rotating its base by the common rotation, the impact force and bay opening can be calculated for any drive-in rack configuration.

It has been shown in Section 3.2 that the maximum bay opening occurs during the first phase of the impact. As reported in the companion paper [20], the forklift truck starts losing contact with the rack after an impact time of 0.15 sec near the end of the first phase of the impact, suggesting that only the first 0.15 sec of the impact needs to be investigated.

In a second approach, the accuracy of the FE model of the rack is checked in conjunction with the FE model of the forklift truck presented in the companion paper

[20] over the critical first phase of the impact in which the forklift truck is still in contact with the rack. The base of the forklift truck model representing the forklift truck body is rotated by the actual amount calculated for test 207 and test 23, and shown in Figure 12. The FE model of the forklift truck is shown in Figure 13 (a), in which k_T and k_B represent the torsional and bending rotational stiffness of the forklift truck mast respectively, C_T represents the torsional damping coefficient and m represents the combined mass of the load, pallet and forks. The mass m is located at the centre of gravity of the pallet load. The values of k_T , k_B , C_T and m used for test 207 and test 23 are given in Table 4. The mast and the forks are modelled using rigid elements. The boundary conditions for the forklift truck are shown in Figure 13 (a). The combined forklift truck and rack FE model is shown in Figure 13 (b). The forklift truck is assumed to impact the rack at the centroid line of the upright.

Figure 12: Actual forklift truck body rotation for test 23 and 207

Figure 13: Abaqus FE model for (a) the forklift truck, (b) the complete drive-in and forklift truck

FE results using the forklift truck model are compared to experimental results in Figure 14 for test 207 and in Figure 15 for test 23. Once again, there is a good agreement for “Impact BC” configuration and a reasonable agreement for “Impact CD” configuration. The agreement found for these two loading configurations is representative of that found for all other impact tests.

Figure 14: Test 207 results - Dynamic Abaqus FE results using the forklift truck model and impact experimental results for “Impact BC” configuration, (a) LVDT 52 and 53, (b) bay opening or d_u

Figure 15: Test 23 results - Dynamic Abaqus FE results using the forklift truck model and impact experimental results for “Impact CD” configuration, (a) LVDT 52 and 53, (b) bay opening or d_u

To conclude, the Abaqus [14] FE model of the tested drive-in rack combined with the forklift truck model provides a satisfactory representation of the experimental impact tests and can be used for parametric studies.

5 Parametric studies

The bay opening reflecting the possibility of a pallet to drop through is related to many variables, including the height of the rack, the design unit load, the loading configuration, the friction between the pallet and the beam rail, the rack depth and the impact elevation. The influence of all these factors is analysed hereafter.

5.1 Rack designs

In order to account for the diversity of drive-in racks encountered in industry, 23 drive-in racks with heights equal to 3 metres, 4.5 metres, 6 metres, 9 metres and 12 metres and unit loads varying from 200 kgs to 1200 kgs (including the pallet mass) are designed in accordance with current industry practice using the proprietary software RAD ([10]) introduced in Section 1.

The drive-in racks used in the parametric study are designed using an 8 bays wide, 4 pallets deep, and 2 bays wide spine and plan bracing configuration. Beam rails are spaced every 1.5 metres in height. Using a sizeable set of uprights, the racks are designed to achieve a maximum action-to-capacity ratio close to 1.0 in RAD.

In order to study the influence of the depth of the rack on the bay opening, two additional 9 metres racks carrying 200 kgs unit loads, 2 and 9 pallets deep, are designed.

5.2 Abaqus models

Scripts in Abaqus are used to create the FE models of the above drive-in racks. The FE models generated using the scripts are based on and have similar characteristics to the FE model described in section 4.1. The base plate moment-rotational stiffness and strength for a given upright width are calculated as reported in [21] from the experimental base plate test results on 125 mm wide uprights described in [18].

In order to limit the number of nonlinear equations in Abaqus and to avoid convergence difficulties associated with large models, the racks are limited to be only 2 bays wide. The impacted upright is the common upright between the 2 bays. The rack is assumed to be sufficiently loaded to ensure that the overall inertia of the rack is much greater than the inertia of the impacted upright. This assumption leads to the overall rack displacement d_o remaining essentially null during the first critical phase of the impact where the bay opening d_u attains its maximum, consequently validating the limitation of the small number of bays of the FE models. In order to simulate the stationary overall rack, the displacement of the uprights at the intersection with the beam rails on one external row is restrained in the horizontal directions as shown in Figure 16.

The forklift is modelled as described in Figure 13 (a) using the characteristics detailed in the companion paper ([20]). The forklift impacts the rack at the centroid line of the front upright at the desired rail beam elevations and is carrying a load equal to the design load of the impacted rack. The base of the forklift truck model is rotated by its mean rotational value given in the companion paper. The centre of gravity of the load is computed at 650 mm from the base of the forks. Figure 16 shows an FE model of a 6 metres high rack with the forklift truck impacting the rack at the second beam rail elevation.

Figure 16: Example of FE model used for the parametric study featuring a 6 metres high, 2 bays wide model, (a) Elevation – side view and (b) top view

5.3 FEA results and impact force

While the maximum bay opening is likely to occur at the impact location, it is obvious that no pallet can be located at the front of the rack at the impact location, since if this was the case, the forklift would not access that particular elevation. Indeed, either the forklift picks up the front pallet and reverses with it to impact the rack, leaving that particular position empty, or the forklift impacts the rack while positioning the pallet, also leaving the front pallet position empty. In the following sections, the maximum bay opening extracted from Abaqus results is always given at a realistic pallet position and is given at the front of this pallet.

In following sections, only maximum bay openings and maximum impact forces extracted from the FE analyses over the first 0.15 sec of the impact are reported.

5.4 Impact at mid height

As mentioned in section 1, the draft specification FEM 10.2.07 [5] requires impact to be assumed at the most unfavourable location, which by engineering intuition would be at mid height of the drive-in racking system. Consequently, the 3 metres, 6 metres, 9 metres and 12 metres high drive-in racks introduced in section 5.1 are impacted at 1.5 metres, 3 metres, 4.5 metres and 6 metres height respectively. The two bays are loaded with one pallet located at the second position from the front, at the impact elevation and in the bay likely to open. For the 3 metres high racks this pallet location is the most critical and only possibility. Even if this pallet location may not always represent the most critical location for higher racks, this location is kept for all rack heights in order to maintain a consistent loading configuration between all tests. Opening is reported for that particular pallet. A coefficient of friction equal to 0.3 is considered between the pallet and the rail beams. Figure 17 plots the bay opening and the impact force against the rack design load for the different heights considered.

Figure 17: Parametric study results – Impact at mid height, (a) bay openings and (b) impact forces

It is observed that the bay opening and the impact force decrease with the height of the drive-in rack. This result, which may be counter intuitive, is mainly explained by the fact that the stiffness of the forklift truck decreases with the height of the impact point due to the constant rotational bending stiffness (k_B) at the base of the forklift truck ([21])

Figure 17 also shows that despite the increase in impact force, the bay opening decreases with increasing rack design load, this effect being more noticeable for short heights. Specifically the decrease in bay opening between the 200 kgs and 1200 kgs pallet loads is 41.1% and 27.0% for the 3 metres and 9 metres racks respectively, while the increase in impact force is 64.6% and 197.3% respectively. For a given rack height, this phenomenon is related to the higher section modulus of the impacted upright and the higher friction forces between the pallets and the rail beams when increasing the design load, both effects providing more resistance to impact.

To summarise, the results show that impact at mid-height is not likely to be the most unfavourable impact location. Particularly for tall racks, impact below mid-height is likely to be critical.

5.5 Impact at different elevations

To further investigate the influence of the impact elevation, the 6 metres and 9 metres high drive-in racks designed to carry 200 kgs pallet loads are impacted at various locations starting from the first rail beam elevation (bottom) to the last rail beam elevation (top). The two bays are loaded with only one pallet, this time located at the front position at the rail beam elevation below or above the impact elevation and in the bay likely to open. Opening is reported for that particular pallet. A coefficient of friction equal to 0.3 is considered between the pallet and the rail beams.

Figure 18 plots the bay opening and the impact force against the impact elevation. It is observed that the bay opening decreases with increasing impact elevation. Furthermore, the bay opening dramatically decreases (by about 59.2%) between impact at the first and second rail beam elevations. The impact force also decreases with increasing impact elevation but slightly increases when impacting the last rail beam elevation due to the proximity of the portal frame beam connection providing additional resistance to impact. Consistent with section 5.4, Figure 18 demonstrates that impact at the first beam rail elevation is critical and is more likely to induce failure than impact at higher elevations.

Figure 18: Parametric study results – Impact at various elevations, (a) bay openings and (b) impact forces

5.6 Impact at constant elevation

The 4.5 metres to 12 metres drive-in racks are now impacted at the first beam rail elevation. The two bays are loaded with only one pallet at the front position, at the

second rail beam elevation and in the bay likely to open. Opening is reported for that particular pallet. A coefficient of friction equal to 0.3 is considered between the pallet and the beam rails. Figure 19 shows the bay opening and the impact force against the rack design load while Figure 20 shows the bay opening and the impact force against the rack height.

Figure 19: Parametric study results – Impact at first beam rail elevation, (a) front bay openings and (b) impact forces

Figure 20: Parametric study results – Impact at first beam rail elevation, (a) front bay openings and (b) impact forces

It is observed from Figure 20 (a) that the bay opening increases dramatically (by between 36.2 % and 67.2%) with the rack height changing from 4.5 metres to 6 metres high but remains approximately constant for higher racks. Figure 19 (a) indicates that for a given height, the bay opening tends to reach a constant value for heavy design loads.

Contrary to Figure 17 (a), where the bay opening decreases with the height of the drive-in rack, the bay opening is relatively impact elevation is constant in Figure 20 (a) reflecting a constant stiffness of the forklift truck. From Figure 19 (b) and Figure 20 (b) it is observed that the impact force increases nearly linearly with the rack height and with the design load.

To summarise, the results show that when impact occurs at the critical first beam rail elevation, drive-in racks taller than 6 metres and designed to carry light loads are more likely to fail than short racks or racks designed to carry heavy loads.

5.7 *Impact against friction coefficient and loading configuration*

As stated in Section 4.1, a coefficient of friction of 0.3 between the pallets and the rail beams was experimentally measured and corresponds to dry and oil-free wood and galvanised steel surfaces. In operating conditions, oil and grease may accumulate on rail beams, thereby reducing this coefficient, and in industrial freezers, the presence of ice may also reduce this coefficient. If the design is performed taking into account friction between pallets and rail beams, it is the designer's responsibility to evaluate the coefficient of friction according to the environmental constraints.

The influence of friction between the pallets and the beam rails is consequently investigated. The 6 metres drive-in racks are used to conduct this study with an impact at the critical first rail beam elevation. Three different loading configurations are considered referred to as "1 pallet", "partially loaded" and "fully loaded". For the "1 pallet" configuration, a single pallet is considered located at the front of the rack, at the second beam rail elevation and in the bay likely to open. For the "partially loaded" configuration, in the bay likely to open, the first and second rail beam elevations are fully loaded except for the front pallet at the impact elevation. For the "fully loaded" configuration, all pallets are positioned on the rack except for the front pallet at the impact elevation in the bay likely to open. Table 5 to Table 7 detail the pallet locations for the three loading configurations.

Opening is reported at the pallet giving the maximum opening, which corresponds in all cases to the front pallet at the second rail beam elevation in the bay likely to open. Figure 21 plots the bay opening against the friction coefficient for all rack design loads and loading configurations. In the presence of friction between the pallets and the rail beams, Figure 21 shows that the loading configuration has a significant impact on the bay opening, this being noticeable even for a small amount of friction. The more pallets, the more horizontal bracing effect of the pallets can be noticed restraining the opening of the bay.

The influence of friction between the pallets and the rail beams on the bay opening is more noticeable when increasing the number of pallets loaded on the rack. While for the "1 pallet" configuration, the drop in bay opening for values of friction coefficient between 0 and 0.3 is between 22.0% and 46.5%, the drop is between 71.1% and 79.0% for the "fully loaded" configuration. As in previous sections, the bay opening decreases with increasing drive-in rack design load.

Figure 22 shows the variation of the impact force with the friction coefficient and the loading configuration. Unlike the bay opening, the impact force increases with the friction coefficient and the pallet load, this phenomenon being related to the rack offering more resistance to impact when increasing the mass and/or the friction coefficient. While the increase in the impact force for friction coefficient values between 0 and 0.3 is between 25.4% and 42.5% for the "1 pallet" configuration, it reaches 66.0% to 104.5% for the "fully loaded" configuration.

Figure 21: Parametric study results – bay opening for an impact at first beam rail elevation on 6 m racks and different loading configurations, (a) 200 kgs design load, (b) 400 kgs design load, (c) 600 kgs design load, (d) 900 kgs design load, (e) 1200 kgs design load and (f) all design loads

Figure 22: Parametric study results – Impact force for an impact at first beam rail elevation on 6 m racks and different loading configurations, (a) 200 kgs design load, (b) 400 kgs design load, (c) 600 kgs design load, (d) 900 kgs design load, (e) 1200 kgs design load and (f) all design loads

In Figure 21 and Figure 22 a difference in bay opening and impact force is observed between the three loading configurations for a friction coefficient equal to 0, particularly for pallet loads of 900 kgs and 1200 kgs. This difference is due to the increasing in base plate rotational stiffness with increasing axial load in the upright, and hence increasing with the number of pallets placed on the rack.

As in previous sections, the bay opening decreases and the impact force increases when increasing the drive-in rack design load.

5.8 Impact and rack depth

To investigate the influence of the depth of the rack on the bay opening, the 9 metres racks 2, 4 and 9 pallets deep, designed to carry 200 kgs pallets loads, are impacted at the first rail beam elevation. A single pallet is placed at the front, at the second rail beam elevation and in the bay likely to open. Opening is recorded at that particular pallet. A friction coefficient equal to 0.3 is considered between the pallet and the rail beams. Figure 23 plots the bay opening and the impact force against the depth of the rack. The results show small changes in bay opening and impact force of 7.2% and 11.2% respectively between 4 and 9 pallets deep racks. The changes in bay opening and in impact forces are more significant between 2 and 4 pallets deep racks, reaching 16.9% for the bay opening and 20.5% for the impact force. The changes can be explained by the larger number of frames in the cross-aisle direction for the deeper racks: there is only 1 frame for the 2 pallets deep rack, 2 frames for the 4 pallets deep rack and 4 frames for the 9 pallets deep. Figure 24 shows the deformed shape for the three racks. The impact force is transferred by shear in the rail beams from the first upright to the last upright, thus ensuring a contribution from all uprights to resist the impact.

Figure 23: Parametric study results – Impact at first beam rail elevation, different rack depths, (a) front bay openings and (b) impact forces

Figure 24: Deformed shapes for 9.0 metres racks of different depths (Top view) – Deformed scale factor = 40.0

6 Conclusion

This paper presents experimental test results from impact tests on a complete full-size drive-in rack structure. A finite element model is calibrated to satisfactorily reproduce the experimental test results and is then used for forklift truck impact parametric studies. The studies show that forklift truck impacts at low elevation are more likely to induce failure than impacts at higher elevation, and that racks designed to carry light pallet loads are more sensitive to impact than racks designed to carry heavy loads. Results also show that for an impact at the first beam elevation, short racks are less sensitive to impacts than tall racks. Moreover, the number of pallets loaded on the rack and the amount of friction between the pallets and the rail beams have a significant influence on the bay opening. Due to the horizontal bracing effect of the pallets and the stiffness of the impacted upright, a high impact load does not automatically lead to a significant bay opening.

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Beam rail elevation	Bay AB	Bay BC				Bay CD				Bay DE
		1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)	
1 st (bottom)	Empty	Empty	Empty	2 tons	2 tons	2 tons	2 tons	2 tons	2 tons	Empty
2 nd		Empty	1.2 tons	2 tons	2 tons	2 tons	2 tons	2 tons	2 tons	
3 rd (top)		Empty	Empty	1.2 tons	1.2 tons	1.2 tons	1.2 tons	1.2 tons	1.2 tons	

Table 1: Concrete blocks location for “Impact BC”

Beam rail elevation	Bay AB	Bay BC				Bay CD				Bay DE
		1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)	
1 st (bottom)	Empty	2 tons	2 tons	2 tons	2 tons	2 tons	2 tons	2 tons	2 tons	Empty
2 nd		2 tons	2 tons	2 tons	2 tons	Empty	2 tons	2 tons	2 tons	
3 rd (top)		1.2 tons	1.2 tons	1.2 tons	1.2 tons	Empty	1.2 tons	1.2 tons	1.2 tons	

Table 2: Concrete blocks location for “Impact CD”

Impact BC		Impact CD	
k_o (kN/mm)	k_u (kN/mm)	k_o (kN/mm)	k_u (kN/mm)
0.762	0.300	0.694	1.124

Table 3: Static stiffness

Test 207, forklift truck characteristic			
m (kg)	k_T (kN.mm/rad)	k_B (kN.mm/rad)	C_T (kN.mm.s ² /rad ²)
1275	148334	873418	1266667
Test 23, forklift truck characteristic			
m (kg)	k_T (kN.mm/rad)	k_B (kN.mm/rad)	C_T (kN.mm.s ² /rad ²)
875	136256	873418	683333

Table 4: Forklift truck characteristics

Rail beam elevation	1 st bay				2 nd bay			
	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)
1 st (bottom)	Empty	Empty	Empty	Empty	Empty	Empty	Empty	Empty
2 nd	Pallet	Empty	Empty	Empty	Empty	Empty	Empty	Empty
3 rd (top)	Empty	Empty	Empty	Empty	Empty	Empty	Empty	Empty

Table 5: Pallet location for “1 pallet” loading configuration

Rail beam elevation	1 st bay				2 nd bay			
	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)
1 st (bottom)	Empty	Pallet	Pallet	Pallet	Empty	Empty	Empty	Empty
2 nd	Pallet	Pallet	Pallet	Pallet	Empty	Empty	Empty	Empty
3 rd (top)	Empty	Empty	Empty	Empty	Empty	Empty	Empty	Empty

Table 6: Pallet location for “Partially loaded” loading configuration

Rail beam elevation	1 st bay				2 nd bay			
	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)	1 st pallet (front)	2 nd pallet	3 rd pallet	4 th pallet (back)
1 st (bottom)	Empty	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet
2 nd	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet
3 rd (top)	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet	Pallet

Table 7: Pallet location for “fully loaded” loading configuration