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INFLUENCE OF PALLET PLACEMENT METHOD ON BEAM BEHAVIOR IN RACK STRUCTURE

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1. Introduction

Selective pallet racks represent a key factor of modern warehouses. The geometry of the structure and the way of load distribution significantly influence the system's mechanical stability. Choosing the right racking structure and its mode of utilization is one of the first things to do in order to properly design the warehouse, making it functional and well organized. Storage systems are a major capital investment whose value depends on the design and how they fit into warehouses and processes, which can also affect the business.

Given the characteristics of pallet racks, typically built from cold-formed thin-walled steel sections, traditional welded or bolted joints are frequently replaced with semi-rigid, boltless connections that enhance assembly efficiency and save costs while keeping structural performance. Accordingly, adjustable storage systems are defined by European standards, such as Eurocode 3 [1]. As the moment-rotation characteristic is essential in describing connection behavior, research on beam-to-column connections has expanded significantly over recent decades, especially in the area of pallet racks [2]. To better understand the strength and behavior under variable loading, various studies, such as [3], have conducted experimental testing of boltless beam-to-column connections to better understand the limit states. In racking structures, placement of unit loads, whether it's transversal or longitudinal against racks, could have a direct influence on structural performance. This paper aims to analyze the effect of beam behavior for various placement methods, relying on the finite element method.

Numerical analysis of beam-to-column connections is used as a reliable tool and as an alternative to experiments in the design of rack structures. In [4] a detailed finite element model was developed for beam-to-column connection, validated through experiment, which simulates moment-rotation behavior without the need for expensive experiments. The stability of semi-rigid connections in racking systems was analyzed in [5], to demonstrate advantages of direct analysis method compared to traditional calculation methods.

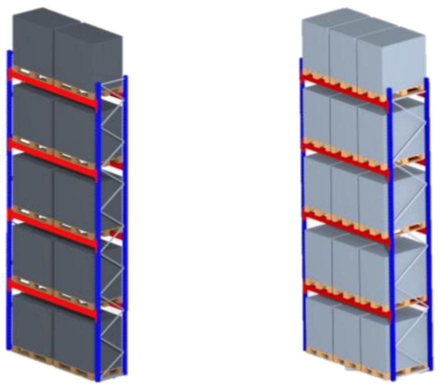
Building upon prior research and integrating techno-economic analysis, this paper investigates how the placement method affects beam behavior in pallet rack structures through Finite Element Method (FEM) analysis in Autodesk Inventor software [6]. Future research should extend contact modeling and boundary conditions to enable a more robust validation and strengthen the reliability of the proposed design recommendations.

2. Techno-economic evaluation

One of the initial steps in designing a warehouse to be functional and well organized is to select the appropriate elements of the racking structure and ensure its optimal utilization. A comparative analysis will be performed depending on the method of unit load placement. Therefore, the design of warehouse with transverse and longitudinal placement will be considered. The design parameters include a storage space with dimensions: length 34500 mm x width 28500 mm x height 7500 mm, entry-exit zones oriented at the same level and on opposite sides, intended for storing unit loads in the form of loaded standard EURO pallets with dimensions: length 1200 mm x width 800 mm x height 1200 mm and a weight of 1000 daN. An electric forklift with a side lift is used as a mean of transport and handling equipment, which determines the loading mode and access configuration for unit loads in each compartment.

According to [7], the techno-economic analysis was conducted based on available input data including space limitations, type of unit load and handling procedure. Analysis considered two different ways of placement with the same beam length: transversal and longitudinal.

With transversal placement, shown in Fig. 1 a), the weaker profile labeled as S80M was selected for the column and the profile labeled as R120L for the beam from [7], with two unit loads placed within a single compartment. The achieved total number of pallet units (capacity) is 1750, with the total mass of the rack structure approximately 37000 kg.



a) **b)**

Fig. 1. Placement method: a) transversal, b) longitudinal [6]

Conversely, with longitudinal placement shown in Figure 1 b), the stronger profile labeled as S80MH was chosen for the column and the profile labeled as R140L for the beam, with three unit loads per compartment. The achieved capacity is 2100 unit loads, with an overall structure mass of app. 28500 kg. Evaluated factors for further analysis are:

- number of unit loads per compartment,
- loads distribution along the beams,
- mass of the rack structure and
- cost of the structure obtained by its mass.

It was determined that longitudinal placement results in better capacity, lower overall structure mass, more rational material consumption and lower costs in the same available space, by the same transport equipment and equal beam span. Having identified longitudinal placement as the techno-economically optimal solution, the numerical analysis explores whether this choice also yields structural advantages by examining beam deformation and field of stress under varying placement methods. This closes the loop between practical application and structural behavior, ensuring comprehensive validation of the design decision.

3. Methodology of numerical analysis

To complement the techno-economic evaluation, the structural efficiency of selective pallet racks was assessed by beam deformation and stress analysis under different unit load placements through FEM analysis. Table 1 summarizes the key parameters for this analysis.

Table 1. Key parameters for placement methods

Type	Placement method	
	Transversal	Longitudinal
Column profile	S80M	S80MH
Beam profile	R120L	R140L
Material	S350GD UNI EN 10346	
Unit loads per compartment	2	3
Load per unit [daN]	1000	
Beam span [mm]	2700	

FEM enables parametric variation of design configurations to assess structural behavior under varying conditions and proper early-stage design development. The finite element mesh generation for both placement methods show a similar number of nodes and elements. That indicates similar discretization needs depending on the direction of load distribution and the shape of contact zones. These set the basis for understanding the results of stress and strain analysis.

Based on data obtained through techno-economic analysis, a solution with longitudinal placement was chosen as the optimal one, with higher capacity and lower overall mass and therefore, lower cost. A comparative study of this data with results obtained through FEM analysis will be performed to verify the solution in terms of carrying capacity.

3.1 Results obtained through FEM analysis

Analysis of beam deformation and stress was realized for a single compartment, i.e., two columns connected by a beam at a defined distance. Due to the limitations in finite element mesh generation caused by the complex geometry of their elements, the analysis was performed as a simplified in-plane frame model to ensure simulation reliability and efficient data processing. Boundaries were defined as fixed for the column bases and frictionless for the internal sides connecting the beam with the column via the beam end connector. The frictionless option is applied to prevent movement in the plane normal to the face where the contact is made.

The entire surface contact between the bottom deck of the EURO pallet and the upper surface of the beam, caused by the transverse placement method, results in a load that is approximated as a uniform pressure of 0,0741 MPa. The deformed model for this method, obtained through FEM analysis, is shown in Figures 2 and 3, respectively.

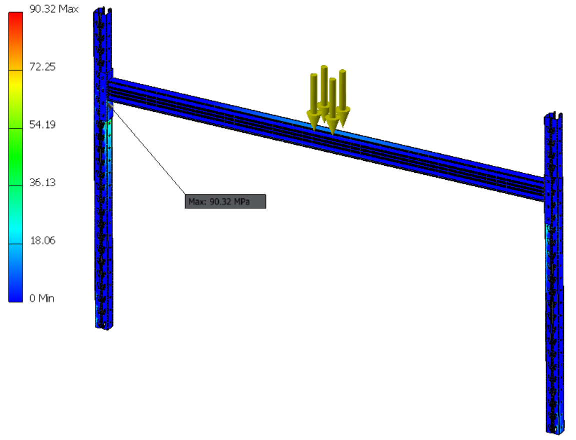


Fig. 2. Von Mises stress for transversal placement

Based on these results, it can be concluded that for transversal placement, as in Fig. 2 and Table 2, the maximum value of the von Mises stress is 90,32 MPa, which is below the maximum yield strength of 350 MPa, indicating that the value is within the elastic limits.

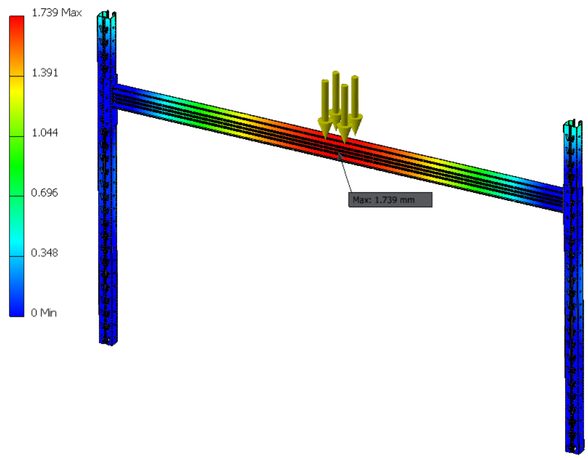


Fig. 3. Beam displacement for transversal placement

A displacement of 1,739 mm, as in Fig. 3, is a beam deformation that does not compromise functionality and is lower than the limit value of 6 mm for the beam profile R120L [7].

The smaller contact between the bottom deck of the EURO pallet and the upper surface of the beam in the longitudinal placement method results in a contact point at the appropriate distance. The beam load is considered as a force of 166,67 daN at each contact point where the bottom deck contacts the beam.

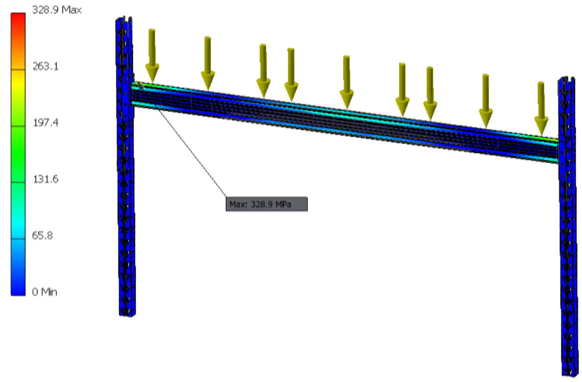


Fig. 4. Von Mises stress for longitudinal placement

The point contact on the beam results in higher stress values, as shown in Fig. 4. The von Mises stress reaches a maximum value of 328,9 MPa but remains below the maximum yield strength of 350 MPa. This indicates the value is still within safe limits, even though the applied load is the maximum load defined for this type of beam.

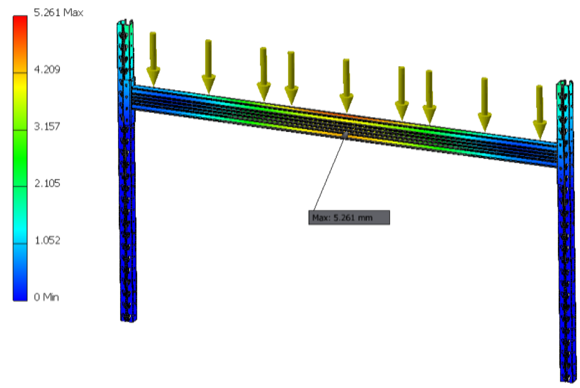


Fig. 5. Displacement for longitudinal placement

Although significantly larger than the transversal placement method, the displacement of 5,261 mm, shown in Fig. 5, does not affect the performance of the structure and it is lower than the limit value of 11 mm for the beam profile R140L [7]. Table 2 summarizes the results obtained through this comparative analysis.

Table 2. Key results obtained in the analysis

Type	Type of placement	
	transversal	longitudinal
Storage capacity [unit load]	1750	2100
Overall mass [kg]	~37000	~28500
Von Mises stress [MPa]	90,32	328,9
Displacement [mm]	1,739	5,261

3.2 Discussion of numerical approach

Since the bracing system in the cross-aisle direction, the opposite side of rack, as well as cross supports for transversal placement, were not taken into account due to the complexity of mesh generation, it is assumed that values would be lower than those obtained if other influential parameters were considered. That affects the maximum value of von Mises stress. Although the results remain within the yield strength, they confirm structural strength under the applied load for transversal placement. For the longitudinal one, significantly high stress values are affected as a result of the idealized contact model, which does not enable such a realistic load distribution. It results in higher deformation, which may be due to local geometric requirements along the support direction, as well as specific load distributions. These differences have a direct impact on the numerical results.

The absence of aforementioned imperfections makes current results slightly conservative, though still within acceptable limits. Despite the valuable insights provided by FEM and techno-economic analysis, it is important to acknowledge that current numerical models involve several simplifications:

- cross support beams are not included, although they are basic elements of transversal placement;
- some contacts are defined as bonded;
- as the static analysis was considered, the absence of other loads and conditions limits the accuracy of the obtained results.

To refine predictive modeling and the practical applicability of the obtained results, the following directions are proposed:

- integration of additional elements to better reflect load distribution and stiffness in racks;
- inclusion of other contact definitions, as sliding or friction, especially in the connection zones;
- expansion of load cases, to cover those not included, which would allow for a more robust validation of the preferred design solution.

4. Conclusions

The integration of techno-economic and numerical analysis confirmed that the placement method is represented as a key parameter in planning the utilization of available space, as well as carrying capacity. The longitudinal placement method represents the optimal solution built on advantages based on storage capacity and reduced mass, thereby enhancing economic and spatial utilization of available space. Additionally, this variant generates higher von Mises stress values and vertical deformations.

Although the transversal placement method exhibits slightly greater mechanical stability under the applied load, its capacity and overall mass do not reach the performance of longitudinal placement. On the contrary, results with significantly lower stress and displacement require heavier construction and its mass, which has a negative influence on the economic efficiency of the system.

Results indicate the need for careful balance between economic requirements and structural reliability. Depending on the project priority, whether it is the maximum capacity, lower mass or reduced deformation and stress, placement method must be strategically aligned with safety and long-term requirements. Although simplified models do not include all structural components, for both configurations beam deformation and Von Mises stress are within the permitted limits. Future research should focus on refining joint behavior, expanding connection modeling and incorporating other loads, to bring the model further to operating conditions and strengthen numerical validation.

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