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Unbraced pallet rack design in accordance with European practice–Part 2: Essential verification checks

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ABSTRACT

This paper concludes a two-parts paper focusing on the design of steel storage pallet racks in accordance with the European provisions EN 15512 “*Steel static storage systems – Adjustable pallet racking systems*”. In part 1, “Selection of the Method of Analysis”,a parametric study has been presented on medium-rise semi-continuous unbraced racks differing for components, geometries and degrees of flexural stiffness of both beam-to-column joints and base-plate connections. The choice of the method of analysis has been discussed, stressing out the influence of both the warping effects and the importance of univocal rules for designers to evaluate the elastic critical buckling loads of the overall frame as well as of the uprights (i.e, the vertical components in racks).

This second part deals with rack design and considers serviceability lateral displacements of the whole rack and both resistance and stability ultimate limit states for the uprights. The different alternatives associated directly with the requirements of the design provisions. or not in contrast with them, have been discussed and applied in order to single out their differences in terms of safety index as well as in the optimal use of the material. Concluding remarks underline the weak points of the European rack standards and are of practical interest for structural engineers, stressing clearly when the recommended procedures fail, hence leading to an unsafe and uneconomic design.

1. Introduction

This paper is the second part of a two-parts paper summarizing the preliminary outcomes of a study focused on the approaches currently adopted in Europe [1] to design steel storage pallet racks. In the first part [2] attention has been mainly focused on the selection of the method of analysis to evaluate internal forces and moments and few alternatives have been discussed. Several configurations of unbraced semi-continuous medium-rise racks, differing for the geometry, for the components and for the degree of stiffness of the joints (both beam-to-column and base-plate connections) were modeled. An open-source finite element (FE) analysis program [3,4] for academic use (Śiva) was used, to which Authors have implemented a refined beam formulation [5–7] able to capture adequately the response of mono-symmetric members commonly used in racks. In particular, the traditional FE beam formulation [8–10], typically characterized by 6 degrees of freedom (DOFs) per node, has been improved by adding the 7th DOF. i.e, the warping of the cross-section (θ), which is essential to model the eccentricity of the shear center with respect to the centroid (Fig. 1). To give a general overview of the cases frequently encountered in routine design, mono- and bi-symmetric cross-section uprights have been modeled, owing to the availability of both 6DOFs and 7DOFs FE beam formulations in Śiva. On the basis of overall elastic buckling analyses, it has been demonstrated that the alternatives offered to designers by European rack standard provisions, or not in contrast with them, could lead to critical load multipliers significantly different from each other, which influence directly the selection of the method of analysis. i.e, the choice between 1st or 2nd order elastic analysis.

In this second part of the paper, few design rules are discussed with reference to both serviceability and ultimate limit states [1,11]. Numerical applications are developed on the same set of racks already presented in the companion paper, to which reference can be made for all the input data related to the geometry of racks and components, as well as to the degree of flexural stiffness of both beam-to-column and base-plate joints, In Fig. 2, both the cross-aisle and the down-aisle views of the considered racks [2] are presented together with the three cross-sections of the uprights. Main results related to the elastic buckling analyses carried out by means of both 6DOFs and 7DOFs beam element formulations have been already discussed with reference to the selection of the method of analysis. Out-of-plumb was considered equal to 1/300 rad for both the down- and cross-aisle directions,

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which has been simulated via additional horizontal forces. It is worth to mention that in routine design practice, out of plum imperfection is applied in each aisle as independent load case. It is authors' opinion that if the design is based on spatial rack models, imperfections have been considered in both the directions at the same time. Furthermore, it should be noted that the modest value of the considered out-of-plumb has a very negligible influence on the research outcomes. Procedures to evaluate the elastic critical load of isolated columns have been introduced and applied to adopt not only for the choice of the analysis method but also for the stability verification checks, as herein shown. The present paper deals with the safety of the different approaches, which can be adopted by rack designers, owing to the absence of a univocal procedure recommended by the European rack Code. For each rack, 2nd order elastic analysis have been carried out, differing for the values of the pallet load considered at the serviceability and at the ultimate limit states. In particular, the multiplier of the 6DOFs buckling analysis (α_{cr}^{6}) was used to define the serviceability load, assumed approximately equal to 0.4 times the value of pallet load activating the overall sway buckling of the rack ($\alpha_s = 0.4\alpha_{cr}^{6}$): it corresponds to a ratio between the critical load and the applied load in service equal to 2.5. Furthermore, considering the value of the amplifying load factor γ recommended by European Code for unit loads ($\gamma = 1.4$) in accordance with limit state design philosophy, the load condition at ultimate limit states was defined, which corresponds to 0.56 times ($\alpha_u = 0.56\alpha_{cr}^{6}$) the value of the elastic 6DOFs FE critical load multiplier (i.e. the ratio between the critical vertical load and the applied load on each rack is approximately 1.8 at the ultimate load condition). Other criteria should be adopted to define the service and ultimate load of the racks: furthermore, it should be noted that the research outcomes discussed in the following are independent on the applied load levels, being the scope of the paper a critical analysis associated with the results of the admitted design options.

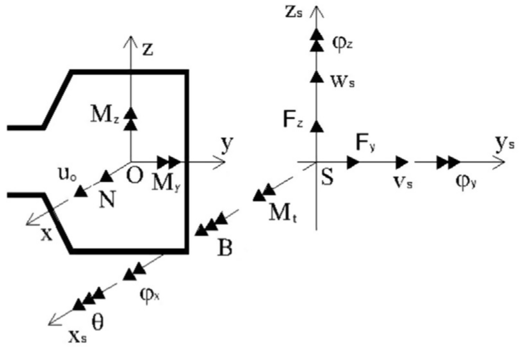

Fig. 1. The set of displacements and internal forces and moments for the finite element beam formulation with 7 DOFs per node.

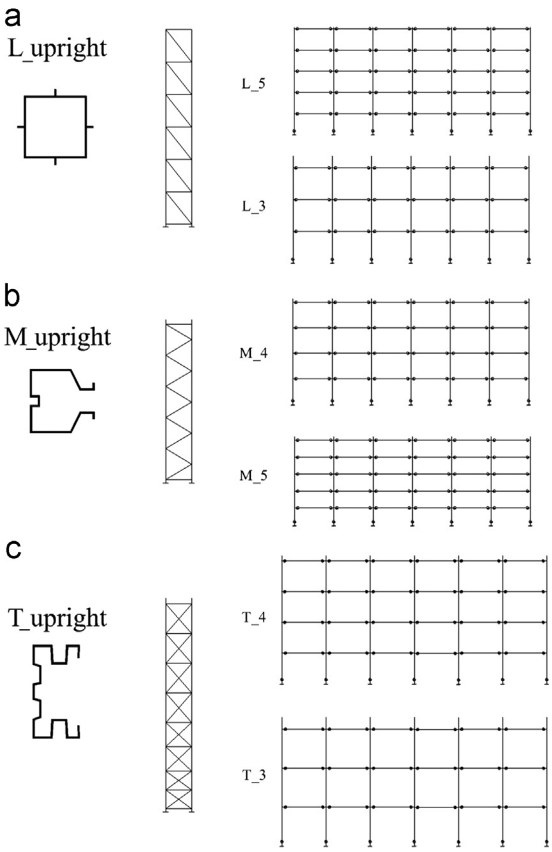

Fig. 2. Essential data of the L_, M_ and T_racks [2] considered in the numerical analysis.

Fig. 3 represents a summary of the verification checks herein considered, which regard to both the serviceability (overall deformability of the rack) and the ultimate limit states for uprights (resistance and stability).

2. Warping influence on the serviceability limit states

Attention has been at first focused on the warping effects of the lateral displacements, and hence only M_ and T_racks are considered, having the uprights with mono-symmetric cross-section. As to the serviceability load condition, reference is made to the 2nd order elastic displacement (δ) at the top of the rack in the down-aisle direction, which in the following is defined as δ^6 or δ^7 (the superscript indicates the number of DOFs adopted in the beam formulation). The influence of warping effects can be directly appraised via the ratio δ^7/δ^6, which is reported in Table 1. It can be noted that increasing the value of the beam-to-column joint stiffness, the 7DOFs displacement is greater than the corresponding 6DOFs one, up to 25% and 37% for M_4 and M_5 racks, respectively. In case of T_racks this influence is more limited, being not greater than 16%, but however not negligible. Furthermore, the influence of the base-plate connection stiffness is quite limited and generally the errors increase with the increase of $\rho_{j,base}$. It appears that the influence of the warping on the top lateral

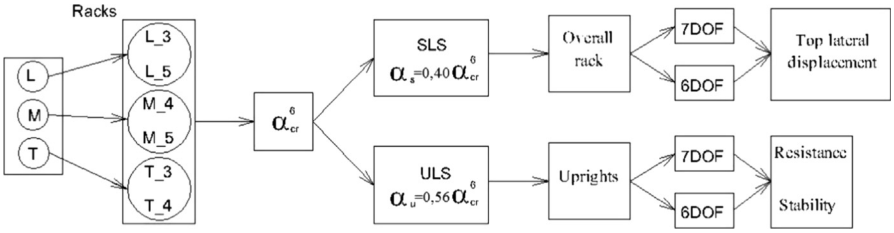

Fig. 3. Flow-charts of the upright verification checks in accordance with the considered design alternatives.