Stability Analysis for Industrial Shelving

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Abstract: *The aim of this work is to set up the methodologies of experimentation on industrial shelves in order to study their mechanical behaviors. This derives from the necessity to support the planning with realistic data, that furnish more certain and suitable safety coefficients. We have concentrated the experimentation on a particular typology of shelf: the Door-Pallet.*
The examined modular elements are constituted by different typologies of columns and different beams (shape and dimensions) but not for technologies of realization: elements obtained by different thickness metallic plates subjected to cold workmanships like cutting, perforation, folding and welding. The column/crossbeam connection has been made by means a particular system of hookup.

Keywords *: buckling, crippling, steel sheets, numerical modelling, stiffness*

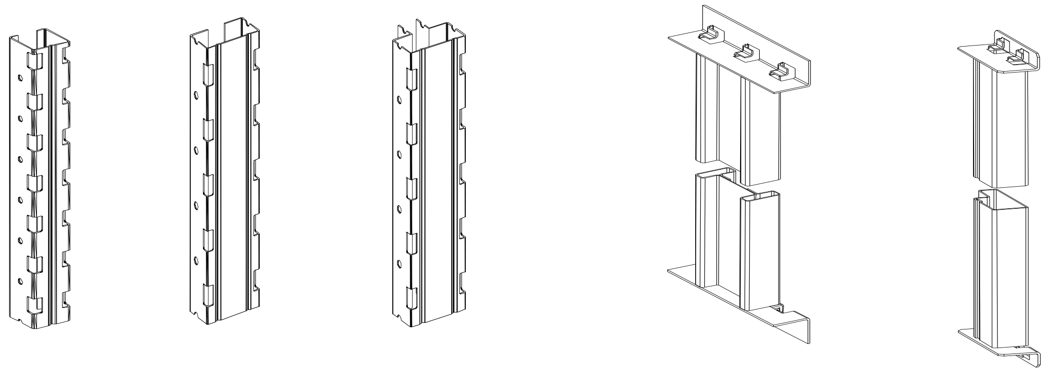
I. INTRODUCTION

Despite the apparent simplicity of the structural behaviour of the modular metallic shelves for stock warehouse (Fig. 1), the accurate evaluation safety factors is based on failure mechanisms typically considered in aeronautical applications.
In these structure typology, columns, due to the modularity required, are obtained by the bending of thin steel sheets with regular arrays of rectangular and circular holes. The problems related to this configuration are the evaluation of the stiffness in the joint column-crossbeam and the evaluation of the safety factors with respect to the columns' buckling and crippling loads. The classic techniques adopted for aeronautical elements subjected to compressive loads [1],[2],[3],[4],[5] cannot be directly used in this case, particularly when holes are localized in the angular section of the profile.
Some typical geometric configuration of the shelf columns were considered and the global buckling load was evaluated by means of a finite element analysis. The columns were modelled using parabolic shell elements. An eigenvalue analysis was performed for the evaluation of the first buckling shape mode and the corresponding load multiplier. The same mesh was used for calculating the equivalent flexural inertia in the principal plane of the section in order to apply the classical Euler's formula.
It was necessary to perform some experimental tests to assess the crippling behaviour. A set of specimens was prepared by mounting a couple of strain gages, on opposite faces of the central plate, at about 1/3 from the end of the specimen, with the aim of determining the local buckling load when the bifurcation of the strain is observed. The methods used are suggested in ref. [5] were applied for the results obtained.
The performed tests were of three types, two of experimental character and one of numerical character:

1. Determination of the joint column/crossbeam's stiffness through bending tests.
2. Determination of the final load capacity for stumpy trunks of columns and the determination of local and global phenomenon of elastic instability (column crushing tests).
3. Calculation of the bending and longitudinal stiffness of the columns through numerical modeling (ANSYS 5.0).

The types of tests chosen resides in the interest to fill the lack of theoretical results and to explore the possibility of placing the numerical simulation and the experimental simulation side by side.

Three families of columns and two families of crossbeams (Fig. 1) constitute the elements used for performing the tests. The mutual combination between columns and crossbeams allows the building of different structures in shape and load capacity.



(a) (b) (c) (a) (b)

columns crossbeams

Figure 1. Tested specimens

II. Stiffness of the Column-Crossbeam Joint

The structure was stressed by a bending load to the extremity by means of calibrated weights in order to obtain an inflexion of the shelf (Fig. 2). The consequent displacements of the current, the angular plate of hookup, and the column in proximity to the hookup zone were measured by means of a system of dial indicators. In total, seven dial indicators were used; three of which to measure the moves of the current one, two to measure the rotations of the column and two to measure the rotations of the angular plate of fixing (Fig. 3).

Figure 2. Loading set-up

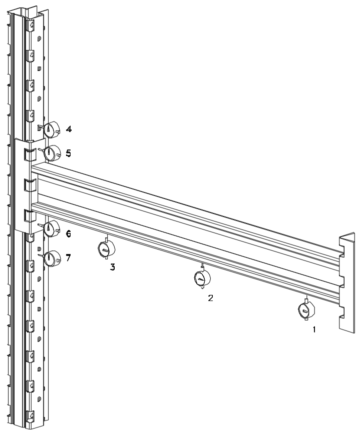


Figure 3. Location of the dial indicators

The dial indicators were fixed to a support structure entirely independent from the load structure with such characteristics of stiffness that made it practically non deformable in comparison to the loaded structure. In this way, it was possible to measure the absolute displacements of the different points.

The elaboration of the measured values allowed us to determine the rotations and, above all, the relative rotations. We were also able to analyze their behavior through the behavior of the reaction moment of the hinge by getting the stiffness of the joint.

In Fig. 4 the behavior of the relative angle α-β1 versus the moment is shown and represents the stiffness of the joint between the trimmer and angular plate of the fixing.

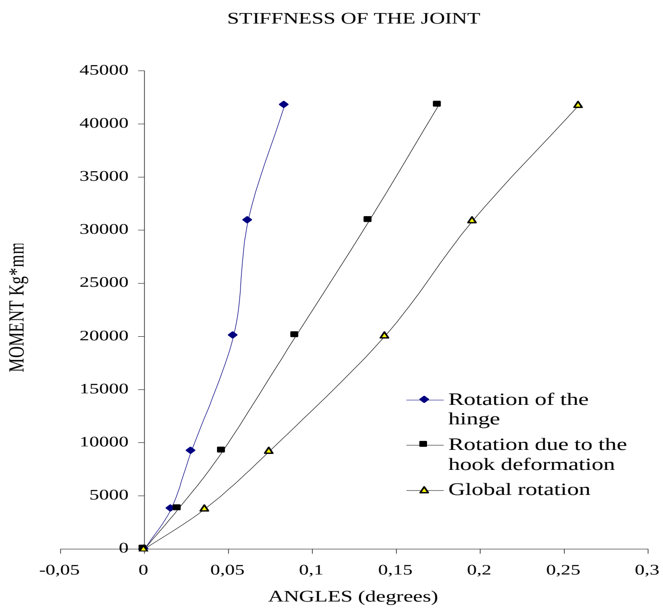


Figure 4. Behavior of the relative angle α-β1 versus the moment

The behavior of the relative angle β1-β2 versus the moment represents the stiffness of the hookup system between tide and column. The behavior of the relative angle α-β2 versus the moment represents the general stiffness of the joint column/crossbeam (general effect). For all the performed tests, diagrams have been drawn similar to the described ones.

III. EVALUATION OF THE FINAL LOAD LIMIT OF THE COLUMNS

The evaluation of the column limit load, in the absence of the phenomenon of global instability such as the peak load, could be esteemed by considering the stress that is equal to the product of the effective specimen section for the admissible tension of the material. In reality, an effected evaluation appears superficial, but above all inadequate because of the extremely complex behavior due to the compression effect. When a column with a section constituted by relatively thin walls is progressively loaded in compression (Fig. 5), for small loads a linearly elastic behavior is obtained and the model can easily be described with the classical theory of the beam. Subsequently, phenomenon of local instability intervenes essentially due to the different local bending stiffness of the flat zones in comparison to the angular one. The problem can no longer be treated with the approach of the mono-dimensional beam theory.

Because of the complexity of the local geometry of the profiled, varied configurations of local instability can appear in sequence or in combination, generically defined with the term *buckling*. It should be noted that a structure subjected to these load conditions can continue to expound its structural function up to the intervention of other phenomena of a real crisis, the condition of *post-buckling*. These phenomena can be in appraising the instant compliance of the compressed element, or much more effectively, measuring the deformations on opposite faces of the thickness of the profiled. Very notable bifurcations of the deformations are present (not visualized in the diagrams since a solitary strain gauge is installed) in comparison to the middle value of the compression. All the described phenomena happen in elastic phase. Unexpectedly, an irreversible yelding of the specimen developed with the formation of folds or discontinuity of the material. This kind of breakup, fundamental in the aeronautical constructions, is called *crippling*. The classic theories for the calculation of the profile subjected to crippling are not applicable to the examined columns because of the presence of slotted holes in correspondence to the angles that sensitively modify their behavior in comparison to continuous sections. The only practicable way to determine the resistance to crippling and therefore, the compression limit load, is to perform experimental tests.

An example of results obtained in the tests are represented in Fig. 6. The two curves have been obtained for different specimen geometry.

Figure 5. Column during the crushing test.

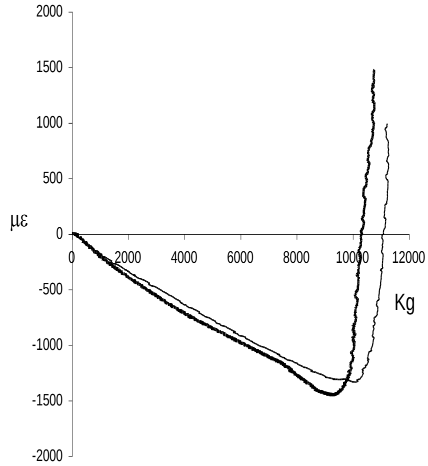
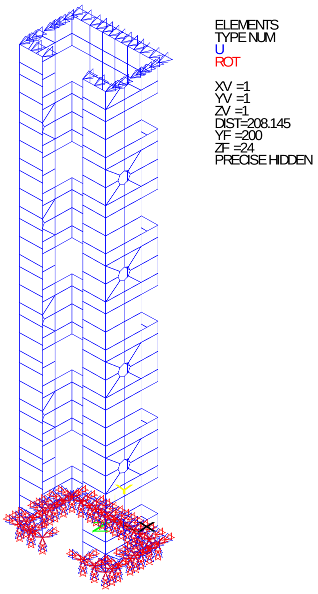


Figure 6. Crippling curve behavior.

IV. BENDING AND AXIAL STIFFNESS

The global elastic instability represents a fundamental condition to consider in order to verify the metallic shelves. Obviously the maximum working load of the structure in relation to the compression efforts in absence global elastic instability must foresee a suitable safety coefficient in comparison to the fracture for crippling. The classic theory of the critical Eulerian load can be applied only if the bending behavior of the column in the two principal planes of bending is known. Since the profiled has slotted holes and holes with constant pitch, it is not possible to easily locate the bending stiffness. It is however, possible to hypothesize that the global behavior of the column is sufficiently homogeneous since it is also in a line not excessively long, and has a systematic repetition of a notable number of equal structural elements. In the case being examined, the method of the finite elements was selected to numerically determine the bending stiffness of the column. The structural schematization is shown in Fig. 7. In order to generate the reference model for the comparative evaluation of the column, a further parametric modeling of the same column deprived of holes and slotted holes was carried out. The models obtained were loaded with an unit and bending deflection. The necessary strength to produce such displacement of extremity was therefore appraised that in the elementary theory of the beam it results proportional to the inertial moment.



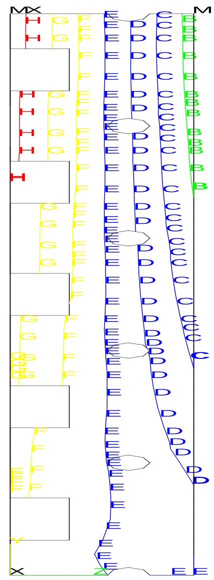


Figure 7. Sructural schematization **Figure 8.** Iso-displacement curves

The obtained results are particularly interesting because they furnish a quantitative evaluation of the effect of the slotted holes and the holes on the bending stiffness of the column. Particularly, the inertial moment around the axle of bending that is parallel to the axle X in the global reference system, is reduced by 26.6% in comparison to the full section, while the one relative to a axle of bending parallel to the axle Z is reduced by 56.8%. Considering that in this plane the inertial moment of the slotted hole section is much bigger, a section that relatively has altogether a homogeneous behavior in the two principal planes of bending is obtained. The difference between the equivalent moments of inertia in the two planes is about 16%. The slotted holes and the hole disposition are such to bring the neutral axle in correspondence of the geometric center of the section. The position of the neutral axle suffers entirely meaningless variations when it passes from the buttonhole zone to the full one, as verifiable from the iso-displacement curves in the axial direction of the profile obtained by the finite elements analysis and shown in figure 8.
The variation of stiffness [6], [7]with normal stress due to the effect of the holes is about 27.8%. Obviously the results were obtained in linear elastic regime and do not depend on the thickness of the profile because the local bending stiffness of the shell does not intervene.

V. CONCLUSIONS

The results obtained by the tests have globally shown that industrial shelves have a structural behavior characterized by multiple non-elementary phenomena such as the non-linear behavior of the structural joints, the rise up of phenomena of local and global instability and the presence of arrays holes and carvings located in groups.

Due to exclusively the particular geometry of the sections and the presence of holes and slotted holes, phenomena as the crippling have been found on the upright ones in correspondence of the not elevated applied loads.

The unreliability of the theoretical methods of calculation to foresee the discussed phenomena and the need to resort to suitable experimentation to increase confidence in the knowledge of the structural behavior was noticed.

The stiffness of the joint column/crossbeam is determined underlining the structural contribution of the single parts of the knot as the beam, the connection, and the column.

In this study, the possibility to appraise with finite elements how the bending stiffness and axial of the columns with the presence of slotted holes change is also underlined.

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