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Stressed Skin Effect on the Elastic Buckling of Pitched Roof Portal Frames

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ABSTRACT

The paper presents the influence of the diaphragm effect on the behavior of pitched roof portal frames, having Z purlins and corrugated sheeting as cladding. The paper highlights the stabilizing effect in terms of load multiplication factor—α_{cr} on portal frames by taking into account the lateral constraints ensured by a typical cladding system—Z purlins with one layer of sheeting panels. The purpose of the paper is to make a comparison between the simplified design model of a portal frame, where the supports simulating the purlins are considered with infinite axial rigidity and a portal frame design model where the calculated stiffness of the cladding for the lateral supports is introduced manually. The obtained results highlight the importance of the diaphragm effect and refer to the variation of the load multiplication factor α_{cr} for main structural elements. The fundamental objective of this research is to develop a relatively fast checking procedure, easy to use in the current design process, by including the diaphragm stiffness in the analysis of the pitched roof portal frames. To evaluate the benefits of stressed skin action, simplified and complex modeling techniques have been developed. Obtained results emphasize the impact of stressed skin action on structural performance of pitched roof portal frames.

1. Introduction

Even since the 1950s, the idea that systems assembled from corrugated sheets, used as roof or wall claddings, which were properly fixed, in addition to their ability to undertake perpendicular loads to their plane, can also undertake loads acting in their planar surface [1]. Loads can be a result of wind action, earthquake and interaction between the frames' claddings or of the diaphragm behavior for certain types of roofs [2]. In all cases, loads applied in the sheeting plane lead to stresses. The resulting stressed membrane is usually defined as a diaphragm. In general, corrugated sheets are subjected to shear forces, while the axial efforts are undertaken by the elements of the transverse frames. This membrane or diaphragm increases the strength and stiffness of the structure and can be used to stabilize structural elements. In Europe, the design methodology using this type of action is called "stressed skin design" [3]—the diaphragm effect. The shear or diaphragm panel refers to one or several corrugated sheeting's separated by structural elements, being part of the shear diaphragm.

In reality, the diaphragm effect is present in a structure, whether it is taken into account or not. Economic studies carried out in Europe by organizations such as the European Convention for Constructional Steelwork (ECCS) or the Constructional Steel Research and Development Organization (CONSTRADO, 1976 [4]) showed savings up to 10% of the total cost of the steel structure, considering the diaphragm effect in design.

For increased efficiency in design, general prescriptions are available for the configuration of diaphragms since the 1980s in Europe. Bryan and Davies [2] prepared recommendations for the size of the panels and gave design rules for the shear and seam connectors and the connections between purlins and bearing structure. Their book includes assembling regulations also. According to these studies, the trapezoidal sheeting instead of the sinus shape is preferred and has better documented references.

Concerning to the testing of shear diaphragms and shear panels, among the first well documented procedures were the ones undertaken by the American Iron and Steel Institute (AISI) in 1987 [5]. Full-scale tests were performed both for regularly in plane shaped models and irregularly shaped ones. Sheet to sheet and sheet to bearing structure fastening tests are presented in the ECCS publications (1978, 1984).

Although a 1977 version of the "European Recommendations for the application of Metal Sheeting acting as a Diaphragm" was published, an improved and better-documented version appeared in 1995 [6]. As recommended in the ECCS publication, the design of structures taking into account the diaphragm effect involves the cladding structure as an integral part of the main load bearing structure and designing it as a diaphragm subjected to shear force, which is mainly used to increase structural stability. Romanian code provisions [7] follow the ECCS recommendations [6].

The primary role of roof and wall cladding systems is to ensure water and air tightness for the building, while the diaphragm effect transforms them into main structural elements. This conversion of secondary structure into primary structural components must keep focus on the usual cladding details, with the typical sheeting thicknesses and the

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Nomenclature

Link element virtual element in ConSteel which connects structural members
MB basic model—initial structural model of the case study without claddings, only minimum required number of purlins added, to run analysis without stability loss
MT1, MT2, MT3 transition models—case study models with purlins added to the basic model (MT1), one additional rotational restraint (MT2), three additional rotational restraints and links (MT3)
ME1…7-SP
equivalent models—improved MT1 models in which the stressed skin effect included using simplified panel configuration rules, 7 different cladding material modeled
SP simplified panel—configured roof panel where a calculated stiffness is imposed; links are connected only to the rafters
CP1, CP2 complex models—improved SP models with additional diagonal links; in the case of CP1 all link elements have imposed stiffness, while for CP2 only diagonal links have imposed stiffness
2L × 1 two sides fastening in every trough
2L × 2 two sides fastening in alternate troughs
4L × 1 four sides fastening in every trough
4L × 2 four sides fastening in alternate troughs
MB1, MT1.1, MT2.1, MT3.1, M1 variations of the models described above in which the number of frames is constant, (16 frames) models developed for different bays (7, 7.5, 8 m)
MB2, MT1.2, MT2.2, MT3.2, M2 variations of the models described above in which the length of the building is adjusted to be similar with reference models, developed for different bays (7, 7.5, 8 m)
flexibility represents the displacement measured in mm obtained when applying a unit force of 1 kN
Stiffness represents the reverse of flexibility and is measured in kN/mm
$\alpha_{cr.beam}$ critical load amplification factor of the design load to cause instability of the beam
$\alpha_{cr.column}$ critical load amplification factor of the design load to cause instability of the column
$\alpha_{cr.global}$ critical load amplification factor of the design load to cause elastic instability in a global mode (as defined in EN 1993-1-1:2005 part 5.2.1), $\alpha_{cr.global} \geq 10$ the frame is not sensitive to 2nd order effects (for elastic analysis)

applied sheet-to-purlin screws and seam fasteners. Starting from these input data and accepting that supplementary measures will generate higher cladding costs, the following questions can be raised:

- How relevant is the type of trapezoidal sheeting in order to account for the diaphragm effect?
- How much is the final stiffness of the diaphragm panels influenced by the way of fastening the corrugated sheeting?
- What is the gain in load carrying capacity if the structure is stabilized by the cladding system, instead of neglecting this effect—expressed in percentages?
- Is it relevant to have a structural design in which the steel sheeting is considered to be acting as a diaphragm, taking into consideration that in most design cases the cladding is not considered as having a structural role?
- How can simple design approaches be developed for taking into account the stressed skin effect?

2. Research objectives

The idea of this study emerged from economical design principles and from the desire to quantify the structural safety reserves using a more detailed analysis of structural elements. The major goal was to find the influence of the roof sheeting acting as diaphragm on the main steel structure, taking the example of an existing structure as a case study.

The analyzed structure is a steel framed industrial hall with simple geometry and trapezoidal sheeting as cladding. The study highlights how the structure works together with the cladding to undertake vertical and horizontal loads and calibrating an automatic computation procedure in a dedicated environment, appropriate in structural design.

There are several analysis parameters to be considered, deriving the following specific research objectives:

- type of trapezoidal sheeting—comparison between the different types of steel sheeting which can be used for the proposed structure, having as variables the corrugation height and material thickness;
- fastening of the trapezoidal sheeting and purlins—every trough fastened or alternate troughs fastened;
- supporting of the shear panels—two or four sides fastening of the shear panel;
- geometric variations of the panel—bay increase reduces the stiffness of the diaphragm;
- methodology of taking into account the stressed skin effect.

The following sections include the assumptions and analysis criteria, computations and obtained results together with their graphical interpretation.

3. Structural configuration using a case study

The above mentioned parameters monitored in this research have been analyzed using a case study on an existing structure located in Oradea, Bihor County, Romania [8]. The focus of this study is to quantify the stressed skin effect, to obtain better design results for pitched roof portal frames with corrugated sheeting as cladding.

3.1. Geometrical and structural configuration of the analyzed structure

The object of the study consists of a single story building. The loadbearing steel structure is made of portal frames with hinged column bases and transverse haunched beams fixed to the columns and horizontal rulers hinged at both ends, placed between the frames. Initial design of the structure neglects the stressed skin effect, where X roof and wall bracings were provided.

The original structure has the following characteristic dimensions:

- Span: 2 × 12.00 m
- Bay: 15 × 6.00 m
- Length: 90.00 m
- Eave height: +6.00 m
- Roof angle/pitch: 8°

The building consists of the office area and the production area (Fig. 1). The office area extends along one bay (6.00 m) and cover the whole span of the hall (24.00 m), while the rest of the space is production area. The office area has two stories separated by a steel floor in dry solution, as shown in Fig. 2. Beams fixed at both ends are located on the perimeter and between the columns, while the rest of the remaining secondary beams are hinged.

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