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Design and optimization of roof trusses using morphological indicators ☆

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ABSTRACT

The adequacy of a structure in strength, stiffness and stability can be evaluated using morphological indicators. This article establishes these indicators for volume, displacement and buckling, for roof trusses. Easy to use graphs then allow to take design decisions at the early stage of conceptual design. Although less precise than computer driven optimization methods, morphological indicators are a simple tool to choose an appropriate typology. In this article roof trusses are added to the morphological indicator theory.

1. Introduction

The search for a reduced use of materials and the quest for optimal structural shape is not new. It is well known that arches and shells acting in compression (under dominant loads) are much more efficient than beams and flat plates acting in bending. The form-finding process for form active structures, both tension membranes and thin compressive shells, always drew the attention of structural engineers. Especially in the design and optimization of shell structures some big names can be cited. The architecture of Wren (e.g. the dome of St. Paul's Cathedral in London, UK) in late 17th century is a paragon of optimal forms. In the 19th century, Gaudi based his repertoire on the principle of the inverse of the hanging model and is famous for his experimental methods to identify the optimal shape. He conceived his art works by creating them as three-dimensional scale models. The Swiss engineer Isler possessed the skill of creating structures with an efficient form acting in pure compression under the dominant loading condition (where the shell's own weight is the dominant loading in shell structures; in thin shells, large bending stresses caused by asymmetric wind loads, can become dominant). It was in 1968 that he created shell structures inspired by the shape of hanging textile using the suspension method by fixating the hanging cloth [1]. A minimum concrete cover is required in order to avoid corrosion of the steel reinforcement [2]. This limits the minimum thickness of the shell. To avoid reinforcement bars, glass fiber textile reinforced cement composites with a high tensile capacity are presently used [3–5]. In this way, the thickness of the shell can further be reduced which enhances the possibilities in lightweight structures. Structural optimization thus became a popular research topic. Also the problem of finding an optimum thickness distribution of steel plate structures to improve the buckling behavior is a key research domain [6].

Structural optimization techniques are not only used in continuum structures. Topology optimization in steel frame and truss-like structures also received significant attention. Several optimization algorithms such as genetic algorithms and gradient search methods (non-linear numerical algorithms) are applied. Jármai et al. [7] proved the suitability of four conceptually different optimization algorithms minimizing the volume of welded I-section frames in the cost function. Merkevičiūtė and Atkočiūnas [8] treat non-linear mathematical models including strength, stiffness and stability constraints of volume minimization problems of structures. The stability constraints for trusses are related to the recommendation of Eurocode 3 [9] for steel design. Pantelides and Ganzerli [10] use the convex model theory, taking into account the effect of uncertainties in load magnitudes and directions, to minimize the volume of a truss and a displacement for a fixed structural volume. The theory can also be applied to frame structures. Stolpe [11] describes the fundamental mathematical properties of discretized structural topology optimization problems. Achtziger and Stolpe [12,13] consider the truss topology optimization and explain the theoretical background, the implementation and some numerical results. The approach of Kawamoto et al. [14] for the optimization problems in terms of the so-called ground-structure approach for truss topology design is used. In the truss ground-structure approach a large set of all potential elements is introduced in the design domain and unnecessary

☆ In honour of my friend Zdenek Bittnar, for his 70th birthday. W. Patrick De Wilde.

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elements are eliminated, or equivalently the necessary elements are chosen, according to the requirements, to obtain the resultant mechanism design.

In a preliminary or conceptual design stage it is however of utmost importance to provide architects with a simple but effective tool to decide upon the optimal topology of a structure i.e. a truss. Morphological Indicators (MIs) serve this purpose.

The use of MI in the conceptual design stage of the design of bridges has proven its usefulness [15,16]. Research on structural morphology started in 1980 with Zalewski's work [17,18]. The link between what will later on be called the geometrical slenderness L/H and the volume (strength) and displacement (stiffness) of a truss was first demonstrated by Zalewski. Quintas Ripoll [19] dedicated part of his work to the optimization of trusses and arches. The shaping of the method of morphological indicators is due to Samyn who studied a large number of structures and expresses their volume and displacement (stiffness) as a function of their geometrical slenderness L/H by means of a dimensionless number called the indicators of volume and displacement [15,20]. A research group on Morphological Design (MoDe), a joint collaboration between P. Samyn and the Vrije Universiteit Brussel represented by co-author of this article W.P. De Wilde, conducted research on this topic. A major contribution to the design approach with morphological indicators is due to the PhD work of Latteur [16] who introduced the influence of buckling. The field of application of the method of Morphological Indicators is further extended by, amongst others, Van Steirteghem [21–23], Verbeeck [24,25] and Vandenbergh [26–28].

Koumar [29,30] recently derived analytical formulas for Pratt, Howe and Warren trusses including the buckling factor as a tool to choose the optimal typology with the criterion of minimizing the volume of a transformable pedestrian bridge. A state of the art of structural optimization using MI can be found in [31].

The novelty of this paper is the extension of the scope of morphological indicators to roof trusses. Both indicators of volume (W), taking into account buckling as a function of their geometrical slenderness (L/H) and indicators of displacement (Δ) are considered. This guarantees a design which is acceptable, even suboptimal (the scope of MI is in the preliminary design phase and involves a number of simplifications; as a result, there is a need for a more detailed calculation), in strength, stiffness and stability.

1.1. Typologies of considered roof trusses

The intention to extend the application domain of MI to roof trusses can be attributed to ecological and economic considerations, especially in developing countries like Kenya. Historically roof trusses in Kenya are made of timber. However because of a governmental ban on logging in order to prevent further deforestation, the price of timber has increased dramatically. Nowadays, even steel roof trusses become competitive. For this reason it is worthwhile to find ways to economise on material use. This can be achieved by making use of morphological indicators during the conceptual design phase.

1.2. Material characterization

From ecological considerations and to avoid further deforestation, steel is preferentially used to replace the traditional timber roof trusses. This article emphasizes the optimal choice of both typology and topology of the roof trusses. In a later phase, a detailed elaboration of the trusses for a given geometry will be published. The choice of the elements taking account of local availability of types of profiles, roofing and based on local climatic conditions (e.g. wind loading) will be further addressed.

1.3. Geometry of roof trusses considered

Fig. 1 shows a number of sketches of simply supported mono-pitch and duo-pitch roof trusses of the Howe, Pratt and Warren type. This research focuses on mono-pitch roof trusses. Samyn [15,20], analyzed plane pinned structures, subjected to vertical, uniformly distributed loads and subject to moving vertical point load. He studied the volume indicator W, and the displacement indicator Δ, thus evaluating strength (excluding buckling) and stiffness. However, all the truss types he considered had a constant height.

Roof angles $15° \leqslant \alpha \leqslant 27°$ are common in Kenya. The scope of the roof trusses are residential and industrial buildings. Spans of maximum 10 m for mono-pitch roof trusses and 20 m for duo-pitch trusses fall within practicable dimensions. Later on the range of geometrical slenderness is limited to $L/H = 8$. For the above mentioned maximum spans, the minimum roof angle thus equals $\alpha = 7°$.

1.4. Load combinations

Four main load cases should be taken into account. The selfweight of the truss and the roof cover, the imposed load for roofs and the wind load. Selfweight and imposed loads are gravitational forces acting downwards. Wind loads on the contrary act perpendicular to the roof cover and thus cause a horizontal component of the force as well. Moreover, both upward and downward acting wind actions can occur. The morphological indicators for the roof trusses presented in the present article are established for vertical loads. This assumption is only valid if the selfweight is rather heavy and overriding the upward acting wind action. If the strength of the truss for the worst case scenario (an upward acting wind action as the dominant variable action) is considered, the combination factor 1.0 on the selfweight and 1.5 on the wind load has to be applied. A compensation of the upward acting wind action is thus only possible in case of heavy roof tiles. It is also worthwhile mentioning that the implementation of horizontal components of forces is beyond the scope of morphological indicators, as the latter is a tool in a preliminary design stage to choose for the best typology for a given span. By including too many different parameters, the complexity increases drastically and thus the aim of morphological indicators is overruled. It is also important to notice that in civil engineering applications such as bridge trusses, this problem of upward acting forces does not occur because the imposed load due to the bridge deck and vehicles are predominant. To the authors' knowledge, studies in literature only present morphological indicators assuming vertical gravitational loads. A distribution of nodal forces resulting from a uniformly distributed vertical load on the top of the truss is thus considered in the present article.

Latteur [16] showed that the ratio between the selfweight of the truss and the applied load is linearly proportional to the volume indicator. The influence of the selfweight of the truss can thus be

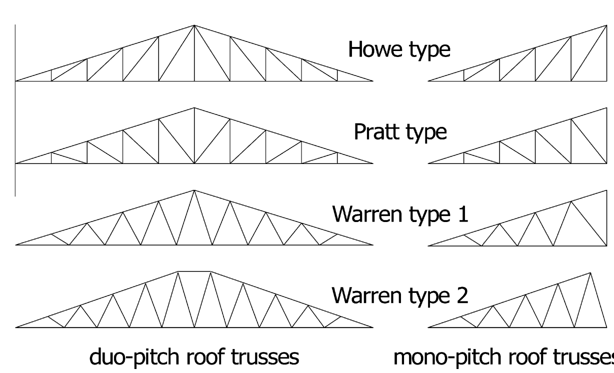

Fig. 1. Roof trusses of the Howe, Pratt and Warren type.