Innovative Tensile Structures for Protected Crop Facilities

Silvana Fuina, Giacomo Scarascia-Mugnozza and Sergio Castellano

Abstract Greenhouse structures are complex buildings that must meet different needs, such as the microclimate control inside the greenhouse, the strength of structural elements, as well as the radiometric and mechanical features of roofing materials. The covering system must allow the transmission of solar radiation for crop needs and guarantee resistance performances in relation to external actions, such as wind and snow loads. Starting from the main characteristics of agricultural commercial greenhouses and tensile structures, the proposal concerns with an innovative tensile supporting structure designed for the covering of protected crop facilities. The innovative tensile structural configuration was first studied by means of the selection of the construction materials and the cross sections of the structural components and afterward calculated using the structural analysis software SOFISTIK. The load analysis on the structure was carried out in accordance with the European standards UNI-EN 13031-1: 2004 and the Italian Technical Construction Code of 2018 related to the Eurocodes. The main results concern the comparison with the current structural types of commercial greenhouses: analysis of the steel weight of the structure and improvement of the structural response to external actions of the innovative tensile structure.

Keywords Greenhouse structures · Load analysis · Structural behaviour

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1 Introduction

Agricultural engineering, with its innovations, contributes to crop productivity by evolving the state of the art in protected cultivation systems. Factors affecting innovation in the sector include labour availability, energy costs, transport logistics, but also factors that arise from regional issues such as environmental impact, product safety and consumer demand. These are sector instances that have the effect of modifying the long-term production system (Giacomelli et al. 2012). In the world scenario the total production area in greenhouses is estimated at around 3,000,000 hectares (Kacira et al. 2016).

In the design of a controlled environment system, such as a greenhouse, structural design, covering systems, environmental control, sustainability and the cultivation system are equally important (Jensen 2002; Scarascia-Mugnozza 2003; Castellano et al. 2005; Russo and Scarascia-Mugnozza 2005; Fuina et al. 2019).

There are researches on technologies for crops in a protected environment that mainly concern the control of the microclimate, the covering materials (Fuina et al. 2016) and the structures (Cepeda et al. 2013; Waaijenberg 2004; Castellano et al. 2006; Castellano and Scarascia-Mugnozza, 1999).

From the construction point of view today the following structural types are used:

- glass or rigid plastic greenhouses are generally built as duo-pitched model or the Venlo type model;
- greenhouses covered in plastic film are generally built as arched shape structure.

This study proposes an innovative and alternative structural typology for greenhouses: a tensile structure that falls within the definition of tensegrity structures, constructions formed by cables and struts. The aim is to study the behaviour of this structural system because it allows large spans and saving of structural material and is characterized by low percentages of shading of the supporting elements.

Inspired by the construction principles of tensile structures already used in other engineering buildings such as sports arenas, airports and shopping centers (Gosling et al. 2013), we designed a greenhouse facility for protected crops.

2 Materials and Methods

2.1 Calculation Methods

The proposed structural module has been modelled using a finite element calculation program, SOFISTIK 2014, program used in previous researches on the structural behaviour of membrane structures and lightweight structures (Gosling et al. 2013; Rank et al. 2005). The finite element method (FEM) used, in the ASE analysis module of the program, is a displacement method, i.e. the unknowns are the displacements values in several selected points, the so-called nodes. The calculation of the

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mechanical behaviour is based on an energetic principle minimizing the deformation energy.

In this method a configuration of n points ordered in a dimensional space is denoted as follows:

$$p = [p_1, p_2, \ldots .p_n]^T \tag{1}$$

A tensegrity structure G (p) is the graph on p where each edge is a cable or a strut. The cables cannot increase their length and the struts cannot decrease. A state of stress ω for G (p) is a state of self-stress if the following condition is satisfied for each node i:

$$\sum\nolimits_j \omega_{ij}(p_j - p_i) = 0 \tag{2}$$

where ω_{ij} is positive for cables and negative for struts.

Satisfying this equilibrium equation is necessary but not sufficient for the tensegrity structure to be in a stable equilibrium configuration. The total functional potential energy should be at a local minimum for a given stable configuration. We define the following "energetic" form associated with the stress state ω:

$$E(p) = \frac{1}{2} \sum\nolimits_{ij} \omega_{ij} \left\| p_j - p_i \right\|^2 \tag{3}$$

The result is a so-called stiffness matrix. This matrix specifies the reaction forces on the nodes of an element when they are subject to known displacements. The balance of the global force is generated on the node in order to determine the unknowns.

Nonlinear effects can only be analysed with iterations. This is done in the program with the Newton method, modified with a constant stiffness matrix. This method detects the residual forces that develop during iterations and calculates the coefficients for the increments of displacement between the current configuration and the previous step.

The loads acting on the structure (Robertson et al. 2002; Scarascia-Mugnozza et al. 2017) were determined in accordance with the UNI EN standards, by the UNI 13031-1: 2004 standard: "Greenhouse: design and construction. Part 1: greenhouses for commercial production".

2.2 *Model Features*

Taking into consideration the structural advantages of tensegral constructions, we set ourselves the goal of designing a "tensile" greenhouse, according to the principles of material savings, reduction of shading due to structural elements, large spans and, therefore, optimization of the functionality and performance of the structure. It was

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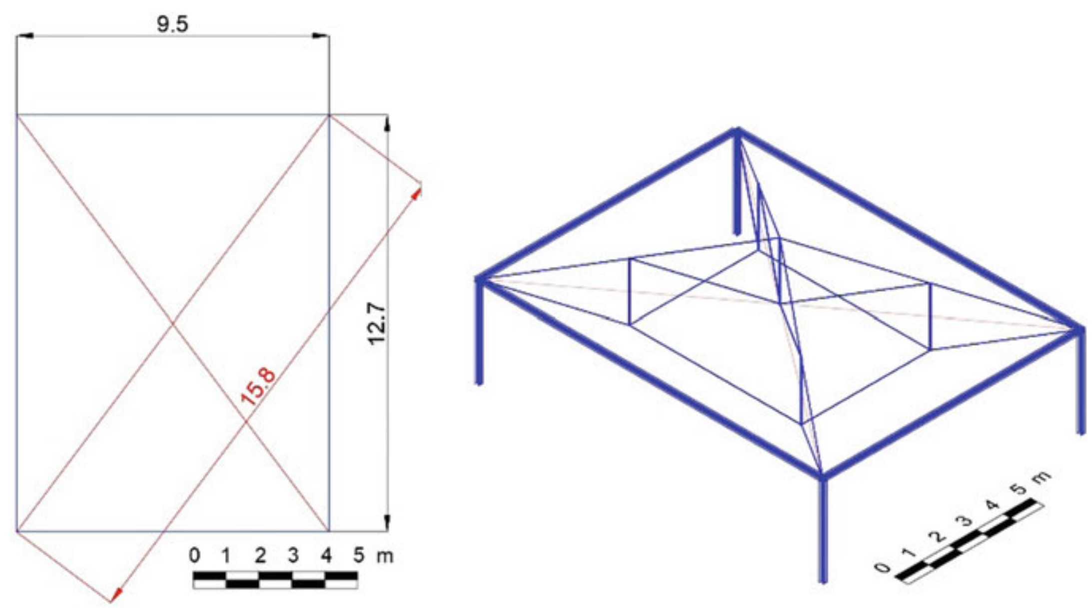

Fig. 1 Axonometric view and plan of the proposed model for the tensile-greenhouse

designed a construction module for greenhouse with the following characteristics (Fig. 1). Basing on the dimensions of the most common structures for commercial greenhouses, the proposed model has the following characteristics: rectangular plan with dimensions 12.7 × 9.5 m and covered surface 120 m^2, with a gutter height equal to 3.5 m and a ridge height of 5.4 m, inclination of the roof flap relative to the horizontal of 15°. The proposed elementary element can be repeated n times to cover surfaces adapted to the production needs of the modern greenhouses settlements.

Rope cables are made of AISI 316 133 stainless steel wire with a diameter of 12 mm.

The bars are in AISI 316 hollow circular section steel, external diameter 44.5 mm thickness 2.9 mm.

The lower frame of the structure, pillars and beams, are in S355 steel with HEA 120 profiles.

3 Results

The greater displacements on the leeward side at the gutter height of the project proposal were analysed and compared with a duo-pitched greenhouse and with an arched shape greenhouse designed having the same covered area and gutter height dimensions (Fig. 2).

The results of the simulations (Tables 1 and 2) show the displacements in millimetres of the selected nodes, in the ULS and SLS combination of load a1, defined by the UNI EN 13031 standard.

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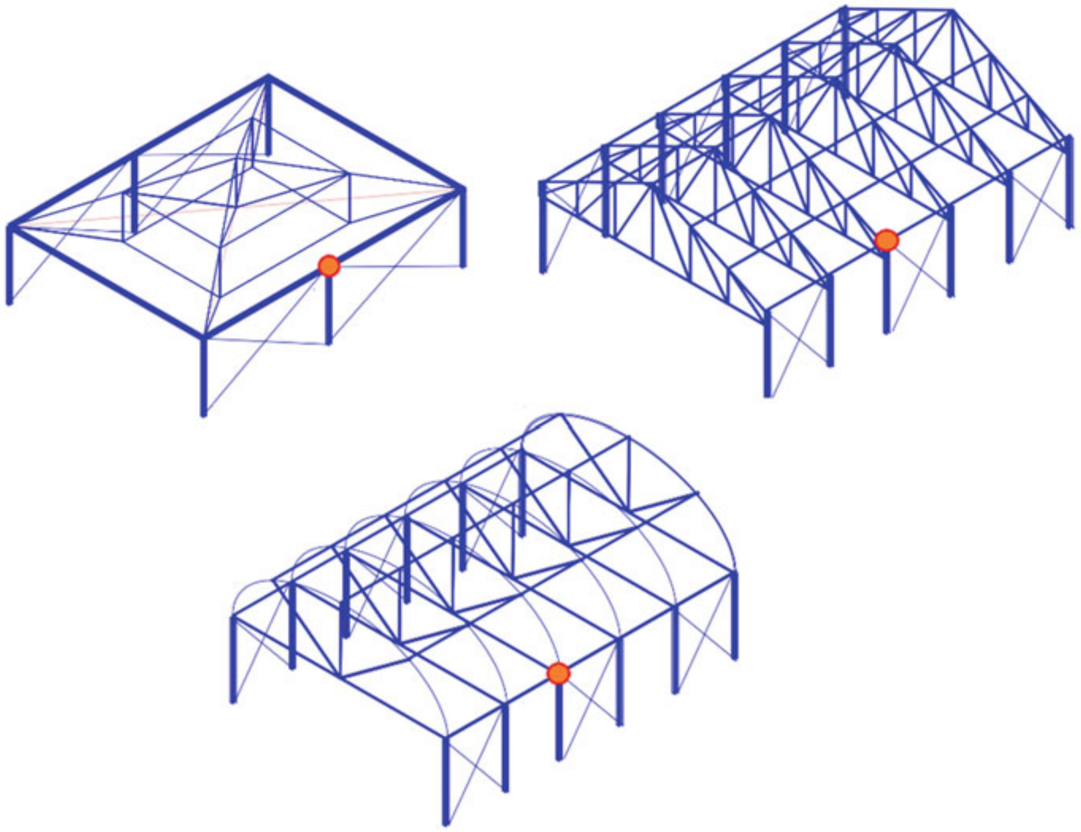

Fig. 2 Selected nodes for the displacements analysis

Table 1 Displacement in the direction of the wind at the height of the gutter of the different greenhouses in a1 ULS combination

Combination	Tunnel	Duo-pitched	Tensile
a1 ULS	63.3 mm	6.8 mm	46.9 mm

Table 2 Displacement in the direction of the wind at the height of the gutter of the different greenhouses in a1 SLS combination

Combination	Tunnel	Duo-pitched	Tensile
a1 SLS	52.8 mm	5.7 mm	39.1 mm

The nodal displacements are asymmetrical due to the non-symmetrical actions of wind and snow. The order of magnitude of the displacements of the tensile greenhouse is not compatible with the project of a glass greenhouse, but rather it is compatible with the displacements of a structure covered by a flexible material (i.e. plastic film).

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4 Conclusion

The aim of this work is the design of an innovative technological typology for greenhouse roofing structures, ideal for the characteristics and functions that must have structures for protected crops. The designed covering structure has the important advantage of a better structural behaviour with regards to external actions that will act on the construction. Future research will focus on improving the structural model of the software and optimizing the structural configuration and sections of the components of the roof.

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