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Research Paper

Finite element model updating of multi-span greenhouses based on ambient vibration measurements

Taehyu Ha [a], Jinwon Kim [a], Bong-Ho Cho [b], Dae-Jin Kim [c], Ji-Eun Jung [c], Seung-Hoon Shin [d], Hongjin Kim [d,*]

[a] POSCO, Seoul, Republic of Korea
[b] Dept. of Architecture Engineering, Ajou University, Soowon, Republic of Korea
[c] Dept. of Architectural Engineering, Kyunghee University, Soowon, Republic of Korea
[d] Dept. of Architectural Engineering, Kyungpook National University, Daegu, Republic of Korea

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Plastic greenhouses are often designed with low levels of safety. As a result there has been an increasing number of structural failures due to abnormal climatic conditions such as heavy snow and strong winds. Standardised prototypes are often used to facilitate the design process, but these prototypes cannot withstand every extreme loading condition. To aid the accurate evaluation of the disaster resilience of plastic greenhouse structures, finite element (FE) analysis for specific load cases is essential in their design process. In plastic greenhouses, clamp connectors and swivel couplers are generally used to connect beams to columns and arched rafters to purlins, and columns are usually driven directly into the ground to support the entire structure. In the FE analysis, however, connections and supports are idealised as fully rigid or frictionless-pinned, which does not accurately reflect realistic conditions. In this study, ambient vibration tests were performed on two full-scale models to identify the dynamic properties of multi-span greenhouses. FE model updating was then carried out to determine the rigidity factors of connections and supports that yield the same dynamic properties as built structures. The results showed that the modelling of connections and supports causes significant changes in modal frequencies. They also showed that the connection modelling condition contributed more to the dynamic parameters of the multi-span greenhouses than the support modelling condition.

1. Introduction

Plastic film-covered pipe-framed greenhouses, also called high tunnels or hoop greenhouses (hereinafter called plastic greenhouses), are used worldwide in agricultural and horticultural sectors. Such plastic greenhouses are typically constructed of curved steel pipes in order to minimise the initial costs, maximise the light transmission, and to reduce the

* Corresponding author.
E-mail address: hjk@knu.ac.kr (H. Kim).
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input of labour. Wittwer (1993) and Lamont (2009) reported that a significant number of plastic greenhouses are used for the production of agricultural and horticultural products in Asia, Europe, the Middle East, Africa, and North America.

As plastic greenhouses are considered to be temporary structures in terms of building design codes, they are usually designed with a lower level of structural safety requirements than permanent building structures (Giacomelli, 2009). However, the number of structural failures of plastic greenhouses is growing particularly due to heavy snow and strong winds, and the economic loss due to their destruction has become a critical problem in the horticultural sector (Moriyama, Mears, Sase, Kowata, & Ishii, 2003; Moriyama, Sase, Okushima, & Ishii, 2015). In particular, the return period of strong winds or super typhoons in tropical zones has recently become shorter owing to global climate change (Kwon, Kim, Kim, Ha, & Lee, 2016). It was reported that in Korea, from 2001 to 2007, a total of 3740 ha and 8516 ha of plastic greenhouses were destroyed by strong winds and heavy snow, respectively (Lee, 2013). As a result, the Korean government has revised the standardised design prototypes for plastic greenhouses to accommodate the recent meteorological data (MAFRA, 2014). These standardised design prototypes include 5 multi-span types, 19 single span types, and 8 long span types for vegetables; and 3 types for fruit trees. The prototypes were originally put forward in 2007 to facilitate the design and construction processes, and were revised four times before their final modification.

These prototypes, however, cannot cover every extreme loading conditions occurring in all regions in Korea. Therefore, finite element (FE) analysis for specific load cases is essential in the design of plastic greenhouse structures for the accurate evaluation of their disaster resilience (Briassoulis, Dougka, Dimakogianni, & Vayas, 2016). In plastic greenhouses, steel-wire buckles, clamp connectors, and swivel couplers are generally used to connect beams to columns and arched rafters to purlins, and the columns are driven directly into the ground to support the entire structure. In the FE analysis, however, cross-linking connections and supports are idealised as fully rigid or frictionless-pinned, which does not accurately reflect actual conditions. Castellano, Candura, and Scarascia-Mugnozza (2004) compared the horizontal and vertical displacements of a full-scale steel greenhouse and showed that the measured displacement values were higher than those calculated from the FE analysis by up to 130%, depending on the assessment of internal connections. Therefore, the exact evaluation of connections and supports is essential in order to realistically represent the behaviour of plastic greenhouse structures.

However, few studies have been carried out to compare the results from mathematical modelling with those from tests on full-scale plastic greenhouses. Ogawa, Tsuge, Sato, Hoshiba, and Yamashita (1990) experimentally investigated suitable support conditions required in the FE analysis using twelve partial sections of full-size greenhouse structures. They concluded that the analytical values determined for fixed supports in the ground support were proper if the arch pipes were inserted into firm and unsaturated ground. A similar conclusion was arrived at by Lee, Lee, Lee, and Kwak (2009) who performed snow and wind loading tests on full-size partial sections of greenhouse structures. However, when a greenhouse is subjected to winds produced by a typhoon they are always accompanied by heavy rain. Therefore, the unsaturated ground condition may not be realistic under these conditions. Furthermore, the foundation of plastic greenhouse structures is often designed empirically instead of following the principles of soil mechanics, and the lack of foundation design requirements was not properly addressed.

Studies on the rotational strength and stiffness of swivel coupler type connections have mainly been carried out on scaffold systems consisting of steel pipes, as they are found in plastic greenhouses. As Godley and Beale (1997) pointed out, a small rotational stiffness of joints can significantly affect the behaviour of scaffold structures. Abdel-Jaber, Beale, Godley, and Abdel-Jaber (2009) conducted a series of experiments on putlog couplers, right-angled couplers, and band and plate couplers, and provided recommendations on the stiffness and moment capacities of the couplers.

Only limited experimental research has been carried out using entire constructed plastic greenhouses rather than partial structures (Moran, 1980; Richardson, 1986). However, the focus of these studies has been on the wind loads acting on the plastic greenhouses, rather than on the structural behaviour of the plastic greenhouses. Further, the majority of the experiments using partial structures have been performed statically. Modal tests to evaluate the dynamic behaviour of plastic greenhouse structures have not been carried to date. A modal test can determine the dynamic characteristics of the structure, such as the natural frequencies and mode shapes, and it can be compared with analytical results in order to evaluate the influence of the modelling strategy. De Brito, Pena, Pimentel, and De Brito (2014) performed a modal test and FE model updating for a temporary grandstand made of a modular scaffold system. They employed spring elements to model the connectors in their analyses, and noted that the modelling of the connections with varying spring constants caused significant changes in the natural frequencies.

In this study, modal tests were carried out on two actual constructed plastic greenhouses to identify the dynamic properties of the plastic greenhouse structures. The ambient vibration test method was utilised for the modal tests, and the output-only stochastic subspace iteration (SSI) and frequency domain decomposition (FDD) methods were adopted to identify the dynamic properties of the structures. The FE model updating was then carried out in order to determine the effect of the rigidity factors of connectors and supports on the dynamic properties of the structure. Several FE models were developed with a progressive degree of refinement in order to evaluate the effect of modelling the connectors and supports on the dynamic properties of the structures by comparing the dynamic properties of the FE models to those of the built structures.

2. Test structures

The plastic greenhouses under investigation were three-span type greenhouses for Satsuma mandarin trees and were located on Jeju, the southern island of Korea. On Jeju, the 10-min-averaged design wind speed, with a return period of 100