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A dynamic-based method for the assessment of connection systems of timber composite structures

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HIGHLIGHTS

- Vibration measurements for the integrity assessment of shear connectors in composite systems.
- Dynamic-based testing and analysis to provide a good alternative to static load tests.
- Experimental and numerical study of timber composite systems.
- The method allows the use of a few mode measurements without compromising good results.

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ABSTRACT

This paper presents a dynamic-based method for the evaluation of connection systems of timber composite structures. The good bonding of the composite elements is crucial for the proper functioning of timber composite structures, as the design capacity and performance of the system cannot be achieved unless an adequate connection condition can be assured. The proposed dynamic method provides an alternative to traditional static load testing and uses vibration measurements to derive a Loss of Composite Action Index, based on an expanded Damage Index method, indicating the reduction in composite action due to the failure of shear connectors. The proposed method is validated on experimental and numerical models of a timber composite beam structure and a timber-concrete composite flooring system. The results demonstrate the effectiveness of the proposed dynamic-based approach that can achieve a good agreement between statically and dynamically derived composite action indicators.

1. Introduction

For the construction of new flooring systems or the upgrading of existing timber floors, timber composite systems, such as timber-concrete composite (TCC) flooring systems, are an attractive alternative to all- timber flooring. Using TCC flooring systems has several advantages such as it enables the upgrading of in-situ timber floors by increasing its loading capacity without the need of demolition [1]. Further, TCC structures can potentially resolve issues of vibration susceptibility and low impact acoustic insulation concerned with light-weight timber floors. While concrete performs well in compression, timber is stronger in tension. In TCC flooring systems, the use of both materials is optimised. The concrete slab is situated in the compression zone and the timber joists in the tension area. Thereby, the timber is used in a similar fashion as steel reinforcement in conventional concrete construction. To transfer shear forces from the concrete slab to the timber joists, shear connectors are essential to provide composite action in the cross-section. Various types of shear connectors are used in practice such as coach or SFS screws, mechanical fasteners or notched connections. Fig. 1 shows an example of a typical TCC flooring system.

For a hybrid timber composite system to function properly and to achieve its design capacity, the integrity of the connection system is crucial as the advantages of the system cannot be achieved unless an adequate shear load transfer can be assured. Hence, in order to ensure a composite system is performing satisfactorily under both, static and dynamic loads, it is essential to reliably assess the condition of the connection system at different stages

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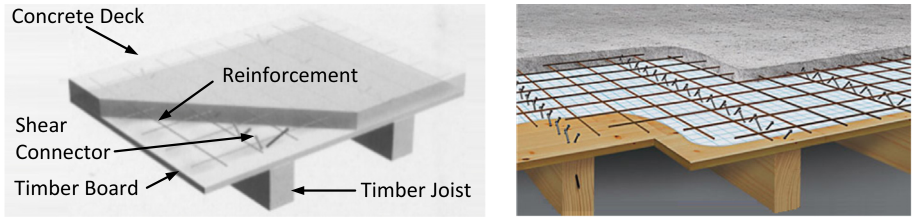

Fig. 1. Typical TCC flooring system [2,3].

during the life span of the system. Traditionally, the composite action of a composite system is evaluated by static load testing using deflection measurements. While the assessment of a composite system using static load testing is possible; for existing flooring systems, such testing is expensive, time consuming and cumbersome to carry out. In addition, already compromised connection systems can get damaged further by conducting static load testing. In order to provide an alternative to the static testing, the research presented in this paper explores the possibility of using changes in the dynamic characteristics of a composite system to assess the condition of its connection system. The basis of such an approach is that damage in a structure, such as the loosening of shear connections, changes not only physical properties of the structure such as stiffness, mass and boundary conditions, but also dynamic characteristics (e.g. natural frequencies, damping ratios and mode shapes). Therefore, by analysing a structure's dynamic properties from structural vibration, any damage, including the failure of shear connectors, can be identified. The research field of vibration-based damage detection is not new, and over the past three decades much work has been undertaken and many algorithms have been developed that are concerned with the damage identification and delamination of structural systems. Comprehensive literature reviews on vibration-based damage detection methods can be found in [4–6]. However, only very limited work has been reported in the area of using dynamic approaches for the composite action determination in timber composite systems and, to the knowledge of the authors, no vibration-based method is currently available that can give satisfactory assessment on the condition of the connection system of timber composite structures.

This paper presents an investigation on using vibration measurements for the evaluation of the shear connection integrity of timber composite systems. The proposed method is based on the Damage Index (DI) method that utilises relative differences in modal strain energy (derived from mode shapes) between an undamaged and damaged structure to locate and quantify damage. In the presented research, the DI method is modified and extended to enable the estimation of the composite action in a timber composite system. To verify the proposed method, it is applied to numerical and experimental models of a timber composite beam structure and a TCC flooring system. For both structures, various scenarios of partial composite action are introduced by removing shear connection elements, and the proposed dynamic method is applied to determine the loss of composite action (LCA) of the timber composite system.

2. Background

2.1. Static-based composite action

The degree of composite action of a composite system is traditionally determined from static load testing using deflection measurements. This testing method is based on the fact that the effective bending stiffness of a composite system is highly dependent on the shear bond coefficient of the interface, referred to as the γ coefficient. A system with $\gamma = 0$ means the layers are acting totally independently and there is no shear transfer between the layers. Such system is known as 'fully non-composite'. This results in a large amount of slip between the layers and large deflection. A flooring system with $\gamma = 1$ represents a homogenous composite action with no slip in the interface and the smallest deflection possible and is termed 'fully composite' [7]. The actual behaviour of a real structural composite system is 'partially composite', i.e. it exhibits a deflection that lies between these two extremes. The degree of composite action is a measure of how close any interconnection comes to achieving the fully composite extreme. Pault [8] quantified the degree of composite action (composite efficiency) based on static test results using the following equation:

$$CA(\%) = \frac{D_N - D_I}{D_N - D_C} \times 100 \quad (1)$$

where $CA(\%)$ is the degree of the composite action in %, D_N is the theoretical fully non-composite deflection, D_I is the measured deflection for partial composite action, and D_C is the theoretical full composite deflection of the system [9]. The resulting static-based Loss of Composite Action (LCA) is therefore defined as:

$$\mathrm{LCA}(\%) = 100\% - CA(\%) = 100 - \frac{D_N - D_I}{D_N - D_C} \times 100 \quad (2)$$

which presents the reduction of the composite efficiency of the connection system,

2.2. The Damage Index method

The Damage Index (DI) method is a vibration-based method used for identifying damage in a structure, including the degree of damage severity. The method utilises differences in modal strain energy (derived from mode shape data) between an undamaged and damaged structure for identification of the location and severity of existing damage. The method was developed by Stubbs et al. [10] and has been successfully applied by various researchers in different fields and applications. Several modifications of the algorithm have been proposed and verified by analytical and experimental studies [11–16]. Farrar and Jauregui [17,18] conducted a comparative study of the DI method, mode shape curvature method, change in flexibility method, change in uniform load surface curvature method and change in stiffness method. These methods were applied to experimental and numerical modal data of the I-40 bridge in Albuquerque, New Mexico; and the DI method was found to be the one that performed the best in terms of accuracy and reliability. Ndambi et al. [19] and Alvandi and Cremona [20] compared Modal Assurance Criterion (MAC), Coordinate Modal Assurance Criterion (COMAC), flexibility and modal strain energy approaches and concluded that the modal strain energy method was the most precise technique among them and also the most stable one when different levels of noise were induced. Some researchers were even successful in the identification of damage at multiple locations [21,22].