ARTICLE IN PRESS

Engineering Structures xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Detection of member overall buckling in civil space grid structures based on deviation in normal strain along the member

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ARTICLE INFO

Article history:
Received 3 March 2016
Revised 11 October 2016
Accepted 17 October 2016
Available online xxxx

Keywords:
Buckling detection
Instability detection
Space grid structures
Space structures
Normal strain

ABSTRACT

A number of structural collapses are initiated from losing stability locally. The monitoring and detection of instability is rarely studied in both research communities of structural health monitoring and structural stability. In order to capture member buckling at an early stage to prevent a local instability from propagating into an overall structural failure, in this study, an approach to detect one type of instability (member overall buckling) is proposed for civil large-scale space grid structures. The foundation of this approach lies in: once a member buckles, a large bending stress due to buckling is developed and dominates the total normal stress of the member. Since the bending stress varies along a member, the total normal stress varies along the member, so does the total normal strain on the surface of the member. Therefore, by identifying the deviation in normal strain at two different cross sections of a member, overall buckling of the member can be detected. This study will justify that strain gauges can pick up all the bending stress induced by buckling as long as they are deployed before buckling. Numerical simulations have been conducted on large-scale space grid structures with different types of connections between members and loading situations. The obtained results have shown that once a member buckles, the strains measured at two different cross sections on the member deviate from each other significantly, verifying the efficacy of the proposed approach.

1. Introduction

In the community of structural health monitoring (SHM) and damage detection, the majority of previous research efforts has been focused on the detection of stiffness reduction of structural members caused by various reasons, such as corrosion, material aging, fatigue or extreme loading. However, the detection of the loss of stability (e.g., buckling), which can easily result in an overall structural failure, has been lacking. On the other hand, the structural stability community has also conducted extensive research. However, they normally focus on how to determine the critical buckling load, and ignore the detection of instability. This research is to bridge the gap between SHM and structural stability research by proposing an approach to detect one type of instability (member overall buckling) for space grid structures at an early stage, which will prevent a local buckling from propagating into an overall structural failure. Space grid structures are usually built to cover venues where hundreds or even thousands of people assemble, and thus detection of buckling of this type of structure to ensure their safety and integrity is significant to improve the safety of the general public.

Indeed, instability is one type of strength limit state in design specifications. However, a number of unknown or unmeasurable adverse factors may lead structures to fail by instability much earlier than expected. For example, in some space grid structures, the ends of the member may be tapered to facilitate a particular type of joint. This tapering may reduce the flexural stiffness of the member and reduce the buckling strength of the member. Also, the use of tee and angle sections may cause the member to be loaded eccentrically, which decreases the buckling strength of the member. Furthermore, some geometric imperfections (initial out-of-straightness, misalignment or lack-of-fit) and material imperfection (particularly with welded joints) that are usually unmeasurable may result in a premature structural failure at loads much lower than those predicted by theory [1]. Therefore, there is

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http://dx.doi.org/10.1016/j.engstruct.2016.10.028
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a strong need to identify local instability timely to avoid a structural failure.

Instability can be classified into static instability and dynamic instability. Static instability can occur under agglomerated snow, ice and other unexpected local or global loads; and dynamic instability can occur under non-conservative loads, such as wind loads or earthquake loads. Depending on the type of structure, static instability for civil space structures can be further classified into individual member buckling and nodal snap-through instability. This study will be focused on individual member buckling. To be specific, it is to propose an approach to detect member overall buckling of space grid structures.

Buckling has often been connected with "a sudden failure" intuitively, leading to the assumption that it is not important to detect buckling, since people have no time to respond even though buckling can be detected in advance. Although a sudden failure happened to an independent single member under axial compressive loading in the laboratory, buckling of a single member in a space grid structure does not mean an immediate collapse of the overall structure due to the fact that there are several members connected at each joint and the structure is redundant. Instead, buckling of a single member can cause the member internal forces to redistribute, and the external loads can then further increase until another member buckles, and so forth until many members buckle, leading the overall structure to collapse [2–4]. Therefore, it is significant to develop an approach to identify buckling in individual members in space grid structures in a timely manner, which will guide the maintenance crew to take measures to prevent individual member buckling from progressing into a collapse of the overall structure.

Although a great number of damage detection approaches have been developed in the field of structural health monitoring, they may not be able to detect buckling. The reason is as follows: member buckling is essentially induced by the softening of local structural stiffness, which is caused by large deformation and/or yielding of local materials, depending on the type of buckling. That is to say, geometric nonlinearity and/or material nonlinearity are introduced when buckling occurs. Therefore, the principle of superimposition of effects does not work here, and thus previous damage detection approaches, which are mostly based on modal analysis, are not applicable here.

Very rarely, research on detecting buckling was reported in the literature. For example, one approach is based on the change in natural frequency. It was proposed based on the following observation: during the buckling testing of an independent single member, as the static compressive load increased, structural natural frequencies gradually decreased; when the load reached the critical buckling load of the member, the first natural frequency of the member decreased to zero [5,6]. Therefore, by tracking the change in natural frequencies identified from measured acceleration responses, buckling can be identified. Unfortunately, for a space grid structure, which is usually indeterminate and redundant, buckling of one member does not usually cause the natural frequencies of the overall structure to change appreciably, not to even mention a decrease of the natural frequency to zero. Qu et al. [7] proposed a two-step approach to detect the buckling of major vertical members in power transmission towers. The first step was to locate the regions of buckling using wavelet packet energy curvature; and the second step was to further locate buckling into exact members using modal strain energy and interval estimation. However, since modal parameters are used here, this approach may be only applicable to cases where the linearity is still valid, which is unfortunately not true for most cases where buckling occurs. Ravet et al. [8] used a distributed Brillouin sensor system to monitor buckling of a steel pipe and column. To initiate buckling, locally thinning the inner wall was applied to two specimens (steel pipe and column). The member was found buckled if the shortening on the whole specimen and elongation in the neighborhood of the thinned wall were detected. By using the broadening factor of the Brillouin spectrum width, the distributed Brillouin sensor system predicted both the magnitude and location of buckling of pipes [9]. This approach is only applied to detect member local buckling. Most recently, Feng et al. detected the lateral buckling of subsea pipelines by mounting the Brillouin optical time domain analysis (BOTDA) distributed sensors on the outer surface of the pipeline. The extracted bending-induced strain is used to indicate the occurrence and evolution of lateral buckling. These newly developed BOTDA distributed sensors has been validated by a series of numerical simulations and experimental testing [10–12]. Ryu et al. [13] developed an FBG strain sensing system based on a wavelength-swept fiber laser (WSFL) to monitor the buckling behavior of a composite wing box. Similarly, Park et al. [14] proposed to detect buckling in delaminated composites by embedding one type of fiber optic sensors (extrinsic Fabry-Perot interferometer) into composites. However, these two approaches require that the FBG sensors be embedded into structural components, which may not be realistic for existing structures.

To bridge the research gap between SHM and structural stability, the objective of this research is to propose an approach to detect overall buckling of individual members in space grid structures automatically, instead of using visual inspection. In practice, for civil space grid structures, they are mostly built as roofs, which are normally located at a very high elevation. Therefore, it is impossible to observe buckling from the ground, even though buckling may produce a significant deformation; In addition, if visual inspection is implemented, it will be very expensive, in terms of equipment to reach the space grid structure (roof), labor and time, and it will affect the normal operation of the building. Therefore, the purpose of this study is to detect buckling automatically using sensors. This way, once member buckling is detected, the obtained detection results will be sent to the maintenance/repair crew immediately to take measures timely before the buckling of the first member leads to the buckling of more members and then the collapse of the overall structure, to avoid catastrophic failures. The buckling type to be detected in this study is flexural buckling. The proposed detection approach in this study is based on the fact that buckling introduces a large bending stress, which leads to the total normal stress to vary significantly along the member. The variation in stress can be reflected in the deviation in strain along the member picked up by strain gauges. Herein the postbuckling behavior of members is taken advantage of.

Considering that nonlinear buckling analyses will be implemented in this study, the following literature was reviewed. To predict the ultimate strength and the related failure mode of thin reinforced concrete shells, a numerical model based on an elasto-plastic-fracturing formulation is developed. In particular, the buckling behavior of two-directional structures was successfully simulated numerically [15]. Through a combined experimental and analytical study, Foraboschi found that geometric non-linear behavior of glass members cannot be described using the same model as steel structures. He proposed a new analytical model to describe the behavior of glass members subjected to combined compression and bending [16]. In addition, Foraboschi investigated the buckling behavior of laminated glass (two layers of glass joined by an elastomeric interlayer to form a unit) numerically and experimentally [17,18]. The obtained results discovered the role of lamination on buckling and provided guidance for using laminated glass as compressive members. To appropriately simulate the nonlinear buckling behavior of space structures, the authors reviewed some related references, for example, buckling/stability analysis of cable-braced grid shells [19,20] and nonlinear stability analyses of hybrid grid shells [21–23] and hybrid barrel vault roof [22,24].