

Identification of Existing Stress in Existing Civil Structures for Accurate Prediction of Structural Performance under Impending Extreme Winds

Tiantian Li¹, Guirong Yan¹, Ryan Honerkamp¹, Yi Zhao¹

Abstract

To accurately predict structural performance under impending extreme winds, it is imperative to identify the existing stressing condition in critical structural components before a hazard (intrinsic stress, referred to as “existing stress” hereafter). The identified existing stress should be added onto the stress induced by future extreme winds in order to determine the real structural performance under these conditions. To identify the existing stress, a novel approach is proposed in this study based on the connection between the unknown existing stress-existing strain curve and the measured stress-strain curve. This approach takes advantage of the known strain information when the material yields. Therefore, an approach to determine when the material yields is also developed. The proposed identification approach does not require any information on previous loads or load effects. Two numerical simulations and one laboratory test are conducted to validate the proposed identification approach. The obtained results demonstrated that the proposed approach is able to identify the existing stress with high accuracy and can be potentially implemented in practical applications.

Keywords

Existing stress identification; intrinsic stress identification; extreme winds; accurate performance prediction; strain measurement

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Introduction

During their service lives, civil structures may be subjected to some extreme winds, such as hurricanes or tornadoes, which unfortunately have resulted in incredible amounts of property damage and significant numbers of fatalities each year. Take hurricanes as an example. Hurricane Andrew violently struck east coast of the U.S. in 1992, causing 65 deaths and property damage of \$27.3 billion (Rappaport, 1993; Blake et al., 2011; NCEI, 2018); and Hurricane Sandy devastated New York and New Jersey in 2012, causing 233 deaths and property damage of \$75 billion (Hewson, 2012; Blake et al., 2013; Diakakis, 2015). Unfortunately, the striking frequency of extreme winds is much higher than some other extreme events, such as earthquakes. In order to save lives and reduce property damage induced by impending extreme winds, it is important to properly predict the behavior and performance of civil structures under extreme wind events, which will lead to appropriate proactive measures that can be used to mitigate such effects.

To predict the behavior and performance of civil structures, the current practice is to apply empirically numerical models of extreme wind loading or to use computational fluid dynamics (CFD) simulations to obtain the wind pressure acting on civil structures, and then employ finite element (FE) analyses with the obtained wind pressure as input to compute structural responses (in terms of stress, strain, displacement and acceleration). The obtained structural responses are assumed to represent the structural behavior under extreme winds. However, an important part of stress (the existing stress developed before an extreme wind event) is overlooked in the current practice. In reality, for existing structures, different types of stresses may have been developed in the structure before extreme winds strike, from such effects as an initial lack-of-fit due to fabrication or installation errors, uneven settlements, air temperature change, dead load and live load. Unfortunately, most of these types of stresses are not measurable or predetermined. However, their effects can be significant. For example, a misfit of 2.5 mm (0.10 in) in a 4.6-m-long (15 ft) member of a three-dimensional steel truss produces a stress of approximately 110 MPa (16 ksi) (Cuoco, 1997). If this is a tension member and this misfit results in a tensile stress in the member, this stress is almost half the yield strength of steel; and if this is a compression member and this misfit results in a compressive stress in the member, this stress may be an appreciable percentage of its critical buckling stress. As another example, the effect of differential settlement in column-supported structures can induce large stresses in structural members. Therefore, if the existing stress in a structure is very close to the strength of the material, a slightly increased wind load may cause the material to reach its ultimate strength. In this case, even though the stress due to the impending extreme wind loading is predicted to be very small, it does not mean that the structure will be able to survive through the event. This may be why some structures collapse during an extreme wind event with a low intensity (see Fig. 1). On the other hand, if the existing stress is very small, even though the stress due to the impending extreme wind loading is predicted to be very large, it does not mean that the structure will fail. In summary, without the knowledge of the existing stress before extreme wind events, the obtained stress from the CFD simulation and FE analysis will incorrectly predict structural performance under extreme winds. Thus, it is necessary to identify the existing stress before a structural performance prediction is conducted.



Fig. 1. Kinzua bridge destroyed by an F1 tornado in 2013 (Photo courtesy to UncoveringPA)

A comprehensive literature review by the current authors shows that no research on identifying the existing stress in existing structures has been reported, while there do exist some approaches on measuring the residual stress induced during manufacturing of metal materials (part of the existing stress). These approaches can be classified into the following four groups: 1) X-ray diffraction method (Fitzpatrick et al., 2005; Larson et al., 1971). It has the appropriate spatial and volumetric resolution to characterize the residual stress distribution. However, the measurement is surface specific and typically can give the residual stress of the top ten microns of the surface; 2) Magnetic Barkhausen Noise (MBN) method (Matzkanin and Gardner, 1976; Wang et al., 2008; Žerovnik and Grum, 2009). It is faster and easier than the X-ray diffraction method for qualitative evaluation, but it requires proper calibration of MBN signal by producing calibration samples of the same steel with known stress state; 3) ultrasonic technique (Javadi, 2013; Javadi et al., 2013; Kudryavtsev et al., 2004); and 4) hole-drilling method (Oettel R, 2000). It is considered as semi-destructive (not non-destructive). To bridge this research gap, this study is to propose an approach to identify existing stress in existing structures without information on previous load effects and without destructing the structure itself. Note that this study will only focus on the illustration and numerical/experimental validation of the proposed approach, not on the prediction of structural performance under extreme winds.

The remainder of this paper will be organized as follows. First, why identifying existing stress before an extreme event is essential for an accurate performance prediction of a structure under the extreme event is discussed; second, a novel approach to identify existing stress in existing structures is proposed; third, numerical simulations on an individual member and on a reticulated space structure are conducted to validate the proposed approach; next, experimental tests on the model of the reticulated space structure are conducted to further validate the proposed approach. Finally, conclusions are presented.

Significance of Identifying Existing Stress for an Accurate Prediction of Structural Performance

Consider a structural component in an existing structure. The existing stress in this component in the current state (called “current stress” and designated as “ σ_{current} ”) can be expressed as

$$\sigma_{\text{current}} = \sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 \quad (1)$$

where σ_1 denotes the stress developed during fabrication, such as the residual stress due to welding; σ_2 denotes the stress developed during member assembling due to fabrication/installation errors; σ_3 denotes the mechanical stress due to the loads or load effects applied before strain gages are installed (e.g., dead load, live load, daily or seasonal air temperature change, and/or uneven settlement loads); and σ_4 denotes the mechanical stress due to the loads or load effects applied after the strain gages are installed (e.g., extra dead load, live load and other impending loads such as snow load, wind load, air temperature change and uneven settlement loads).

Assume that strain gages are the only measurement instrument deployed on the structure. It is well-known that a strain gauge can only capture the strain induced by the loads or load effects applied after the strain gauge is deployed. For an existing structure, among all the four types of stresses, only σ_4 can be measured and obtained, which is referred to as “measured existing stress $\sigma_{m_existing}$ ”. The associated strain that can be directly measured from a strain gauge is called “measured existing strain $\varepsilon_{m_existing}$ ”. However, the other three types of stresses (σ_1 , σ_2 , and σ_3) cannot be measured. Unfortunately, the sum of them ($\sigma_1 + \sigma_2 + \sigma_3$) can be significant, which is referred to as “unknown existing stress $\sigma_{unk_existing}$ ”. The associated strain is called the “unknown existing strain $\varepsilon_{unk_existing}$ ”. Then, Eq. (1) can be rewritten as

$$\sigma_{\text{current}} = \sigma_{unk_existing} + \sigma_{m_existing} \quad (2)$$

Accordingly, the strain in the current state, $\varepsilon_{\text{current}}$, can be expressed as

$$\varepsilon_{\text{current}} = \varepsilon_{unk_existing} + \varepsilon_{m_existing} \quad (3)$$

To justify the significance of unknown existing stress in structural components, a civil space structure made of steel is taken as an example. Consider an individual member (See Fig. 2) in this space structure. Assume that the member is 4 m long ($l = 4 \text{ m} = 13.1 \text{ ft.}$). If the member is fabricated with a length error, say, 2 mm shorter ($\delta = 2 \text{ mm} = 0.08 \text{ in.}$), the ratio of δ/l will be 1/2000. By applying the relationship between the stress induced by the fabrication error and the ratio of δ/l (Boresi et al., 1993)

$$\sigma = \frac{E\delta}{l} \quad (4)$$

this small fabrication error yields a tensile stress of 104.5 MPa (15.2 ksi), with the Young’s modulus (E) of 209 GPa (30,313 ksi). If the residual stress developed during manufacturing and the stress due to the dead load, live load and other related load effects are considered, the current stress may reach a very large value. This example demonstrates the existence and significance of existing stress.

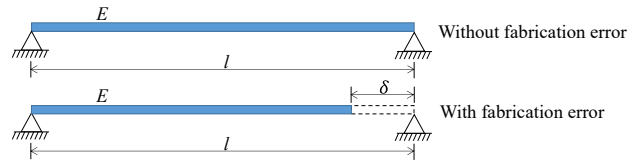


Fig. 2. Fabrication/installation error yields significant stress in a structural member

Previous studies also demonstrated the necessity to consider existing stresses in structures. Javadi (2013) measured residual stress in stainless steel pipes due to welding using ultrasonic measurements and it was found that the residual stress around the weld centerline can be as high as 150 MPa (21.7 ksi), which was around 88% of its yield strength (170 MPa or 24.6 ksi). The X-ray diffraction method and MBN method were also applied to investigate the residual stress in welded structures and it was concluded that tensile residual stresses were generated at the welds due to the thermal contraction of the weld steel and the adjacent heated parent material during cooling after welding and that these tensile residual stresses can reach as high as the yield strength of the weld steel or the parent material (Fitzpatrick et al., 2005; Gur, 2018; Lachmann et al., 2000; Leggatt, 2008; Matzkanin and Gardner, 1976). Banahan (2008) investigated the structural integrity of a nuclear power-generating plant by including residual stress in his analysis. The magnitude of the von-Mises residual stress was evaluated as 52 MPa (7.5 ksi) and the membrane residual stress as 41 MPa (5.9 ksi). The finite element collapse analyses showed that the results were significantly different when the residual stress was included as existing stress, demonstrating the influence of existing stress on the accuracy of structural integrity assessment.

Based on the demonstration example and previous research, the knowledge of the unknown existing stress is crucial to properly predict the real loading conditions experienced by a structural component. Thus, it is imperative to identify the unknown existing stress in existing structures, which justifies the significance of the proposed research.

Proposed Approach to Identify the Existing Stress before an Extreme Wind Event

An approach to identify the unknown existing stress in existing structures is proposed in this study. The fundamental idea of the proposed approach is described by taking a beam as an example.

Fundamental idea of the proposed identification approach

Assume that a strain gauge is deployed on a beam during the service life of the structure (e.g. 10 years after the structure was built). Then, the strain of the beam induced by external loads or load effects after the strain gauge is deployed can be measured by the

strain gauge, that is, $\epsilon_{m_existing}$ in Eq. (3). Assume that the structural material still works in the linear, elastic regime at that stage, the measured stress-strain curve (Line AC in Fig. 3(a)) can be built on the existing stress-strain curve. Note that the existing stress-strain curve is not known in practice. The origin of the measured stress-strain curve is set as “A”. This figure illustrates that the measured strain/stress does not include the unknown existing strain/stress and that the current strain/stress is the sum of the unknown existing strain/stress and the measured existing strain/stress. Since previous loads and/or load effects are not completely known, the other two terms, $\epsilon_{unk_existing}$ and $\epsilon_{current}$ in Eq. (3) are unknown. Therefore, $\epsilon_{unk_existing}$ cannot be solved from Eq. (3). However, there exists one time instant when $\epsilon_{current}$ is known. If the limit state of the member is material yielding, this time instant will be when the material yields, as shown in Fig. 3(b). At this time instant, $\epsilon_{current}$ is the yield strain of the material. This time instant is taken advantage of to reduce two unknowns in Eq. (3) to one unknown. Then, $\epsilon_{unk_existing}$ can be directly solved from Eq. (3).

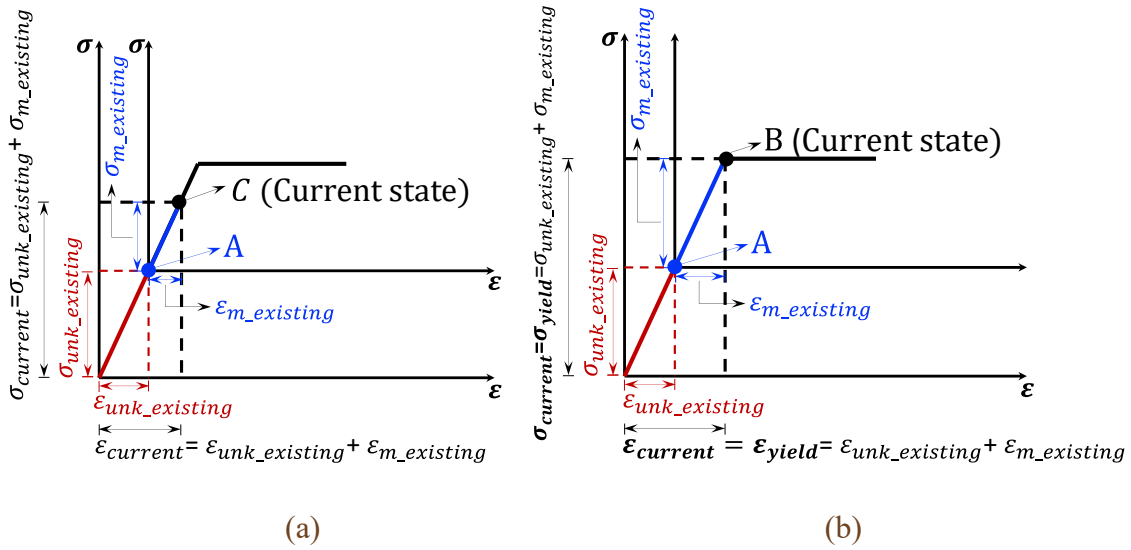


Fig. 3. Relationship between the unknown existing stress/strain and the measured existing stress/strain in stress-strain curve: (a) Stress and strain at any time before yielding, (b) Stress and strain at yielding

To illustrate this idea, a beam (see Fig. 4(a)) is taken as an example. Assume that the loads or load effects applied onto the beam are not known (designated as “Previous Load” in Fig. 4(a)). To identify $\epsilon_{unk_existing}$, first, deploy a strain gauge at the bottom of midspan of the beam. Then, apply an extra live load (designated as “Added Load” in Fig. 4(a)) to force the very outmost fiber at the midspan of the beam to yield. Then, $\epsilon_{m_existing}$ in Eq. (3) will be the reading of the strain gauge at yielding. The $\epsilon_{current}$ at yielding can be obtained from the information provided in the material manual. Take A36 steel as an example. The yield stress is specified as 248.2 MPa (36 ksi). Then, the yield strain can be calculated depending on the loading situation. It is 12.41×10^{-4} ($248.2 \text{ MPa} / 200,000 \text{ MPa} = 36 \text{ ksi} / 29,000 \text{ ksi}$) under uni-axial loading. With $\epsilon_{m_existing}$ and $\epsilon_{current}$ obtained, $\epsilon_{unk_existing}$ can be directly solved from Eq. (3).

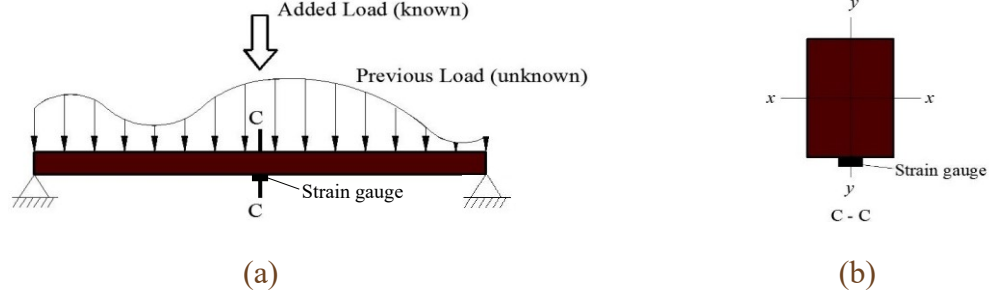


Fig. 4. A demonstration of implementing the proposed identification approach: (a) A schematic diagram of a beam with added load, (b) Zoom-in figure of Cross-section C-C in Fig. (a)

By the time when the very outmost fiber of the beam reaches yielding, the linear relationship between stress and strain can still be applied, although the linear relationship becomes approximate after the proportional limit stress. Therefore, once $\varepsilon_{unk_existing}$ is obtained, $\sigma_{unk_existing}$ can be estimated based on classic Mechanics of Materials. A different type of “Added Load” may be used for a different type of structure. For example, for a bridge, the “Added Load” can be traffic load; and for a civil space structure, the “Added Load” can be extra weights.

Determine when the material yields

When implementing the proposed identification approach, the key point is to determine when the material yields. Two approaches are proposed in this section to determine when the very outmost fiber of a structural member yields.

1) Based on the load-strain curve. When identifying the existing stress, the applied “Added Load” is known. Accordingly, $\varepsilon_{m_existing}$ is known, since it is the reading of the strain gauge. If $\sigma_{m_existing}$ can be calculated, the solid black curve in Fig. 3 can be obtained. Once Point B is reached, it indicates that the material has yielded. Unfortunately, $\sigma_{m_existing}$ cannot be calculated, since it is unknown when the linear relationship between stress and strain ends. Therefore, when applying this approach in practice, the magnitude of the applied “Added Load” should be increased gradually; and at each load step, the “Added Load” is kept the same for a while to see if the measured strain is increasing. If the material has not yielded yet, the measured strain will be constant or approximately constant as time evolves; and if the material yields, a continuously increasing strain will be measured. Based on this, the load step when the material yields can be identified.

2) Based on the $\Delta Load / \Delta Strain$ ($\Delta F / \Delta \varepsilon$)-step curve. It is well-known that the material yielding can be indicated by the drop of E of the material, as shown in Fig. 5(a). Herein, since the $\sigma_{m_existing}$ cannot be obtained, E at each load step cannot be obtained, and thus Fig. 5(a) cannot be constructed using the measured data. However, the $\Delta F / \Delta \varepsilon$ -step curve at each load step can be obtained (see Fig. 5(b)). The yielding point can be indicated by a sudden drop in the $\Delta F / \Delta \varepsilon$ -step curve. When applying this approach, first record the applied “Added Load” at each step and the strain measured at the associated load step; and then calculate the change in “Added Load” and in the measured strain,

respectively, between two consecutive load steps. The obtained data will be used to construct a $\Delta F/\Delta \varepsilon$ -step curve (Fig. 5(b)). The sudden drop observed in the $\Delta F/\Delta \varepsilon$ -step curve indicates that the material yields.

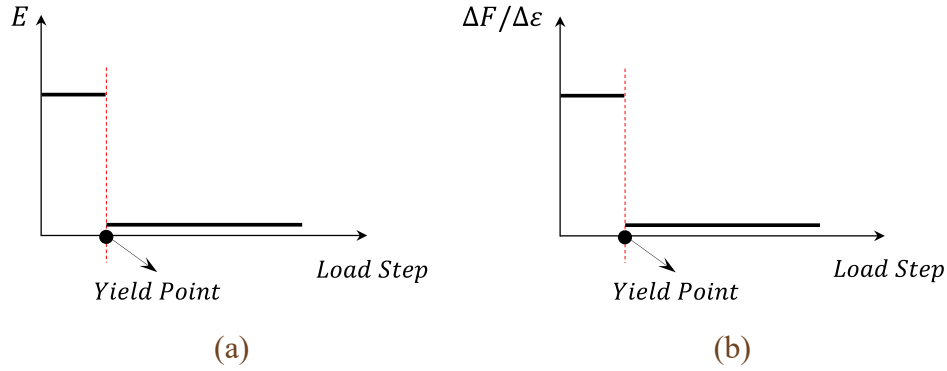


Fig. 5. The illustration of the approach to identify when the material yields: (a) E drops when the material yields, (b) $\Delta \text{Load}/\Delta \text{Strain}$ drops when the material yields

Once the time instant of yielding is identified, the reading of the strain gauge at that time instant will be used as $\varepsilon_{m_existing}$ and the yield strain of the material will be used as $\varepsilon_{current}$ in Eq. (3). Then, the $\varepsilon_{unk_existing}$ can be solved from Eq. (3). Accordingly, $\sigma_{unk_existing}$ can be calculated. Once the identification of $\varepsilon_{unk_existing}$ is completed, the temporary “Added Load” will be removed. Then the identified stress will reflect the current stressing condition of the member, which is the existing stress (can be also called “intrinsic stress”) in the existing structure. The whole procedure of identifying the existing stress is presented in Fig. 6.

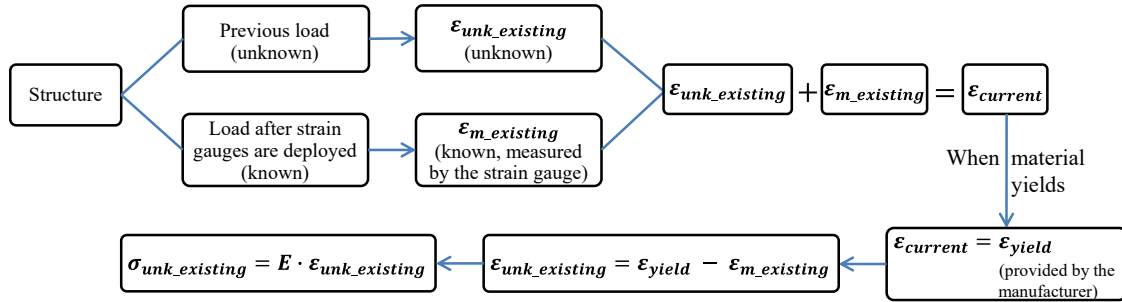


Fig. 6. Flowchart of the identification of the existing stress

Discussion on the Implementation of the Proposed Identification Approach

By applying this approach, all the unmeasured or unmeasurable loads and load effects applied to the structure previously can be reflected from the identified $\varepsilon_{unk_existing}$ and $\sigma_{unk_existing}$, which will facilitate in obtaining the real stressing condition of the structure. Only the real stressing condition can tell whether the material will reach its

limit state soon or not. If it will, a slightly higher load may induce the material to reach its ultimate strength. It means that the chance for this structure to survive through an impending extreme event will be low. If the existing stress in the structure is very small, the structure can resist more loads and may survive through an impending extreme event. In this sense, the identification of $\varepsilon_{unk_existing}$ and $\sigma_{unk_existing}$ is crucial for proper prediction of the behavior and performance of a structure under impending extreme wind events.

Normally, one is more interested in the existing stress in the most critically stressed structural component, the component with the maximum stress. By applying an appropriate “Added Load” to the structure, the existing strain and stress in that component can be obtained.

In the illustration in Fig. 5, the material is assumed to be ideally elastic-plastic. In fact, as long as the material yielding causes the Young’s modulus (E) to reduce (not necessarily has to be ideally elastic-plastic), the proposed approach will work well.

In the example illustrated in **Section Fundamental idea of the proposed identification approach**, the “Added Load” will cause the very outmost fibers to yield, leading to a certain level of damage to the beam, although it is minimal in this case. To avoid this damage, an extra layer or piece of material can be attached onto the original member, as shown in Fig. 7. The strain gauges can be deployed on the side of the original member and at the bottom of the extra layer/piece of material. Considering that the stress in the current state is normally no more than 60% of material strength, a preliminary FE analysis can be conducted to find the magnitude of the “Added Load” that can lead to 40% of material strength. The obtained magnitude of the “Added Load” can be the starting point of loading. The magnitude increment can be uniform at the beginning and gradually decrease in order not to miss the load magnitude that just causes the very outmost fibers to yield.

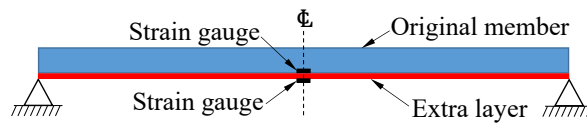


Fig. 7. Attaching an extra layer of material to avoid damage during the test

In the analysis and discussion in **Section Proposed Approach to Identify the Existing Stress before an Extreme Wind Event**, it is assumed that the limit state of the structural component of interest is material yielding. For the cases where the limit state of the component is buckling (instability), the time instant when the measured strain is used as $\varepsilon_{m_existing}$ in Eq. (3) will be when the member buckles, and $\varepsilon_{current}$ is the buckling strain of the material, which can be calculated from the design critical buckling stress and Young’s modulus of the material. How to determine when the member buckles can be referred to Yan et al. (2017) and Yan et al. (2018). As long as it is elastic buckling, once the “Added Load” is removed, the deformation due to buckling will disappear and no damage will occur due to this identification process.

Numerical Simulation

To validate the proposed identification approach, numerical simulations have been conducted at the member level (a beam) and at the structural system level (a reticulated space structure).

At member level

Consider a beam (Fig. 8). It spans 4.6 m (15 ft.). Assume that it is made of W12×22 of A36 steel. The Young's modulus of the steel is 200,000 MPa (29,000 ksi). Assume that the constitutive law of this steel is ideally elastic-plastic. Assume that the member is manufactured 2.54 mm (0.1 in.) shorter than being designed due to the fabrication error, and all previous applied loads and load effects can be equavalent to the action of a uniformly distributed load of 0.9 N/mm (5 lb/in.), which introduces the existing stress into the member. It is noted that the shortening of 2.54 mm (0.1 in.) of the member creates tensile stress in the member. A two-dimensional FE model is developed in ABAQUS using linear line elements (B21). Through a static analysis (forward analysis), the stress and strain at the bottom of the beam at midspan are obtained as 116.549 MPa (16.904 ksi) and 5.829×10^{-4} , respectively, which are the targets of the identification.

The existing strain and stress at midspan will be identified by numerically simulating a test. In this simulated test, a concentrated live load (designed as “Added Load” in Fig. 8) is applied at midspan of the beam, and a strain gauge is assumed to be deployed at the bottom surface of the midspan to measure the strain induced by the “Added Load”. The magnitude of the “Added Load” is increased gradually. At each load step, a nonlinear static analysis is conducted to obtain the pre- and post-yielding behavior, and the load increment and the strain at midspan are recorded. The obtained load and strain data are used to construct a load-strain curve (Fig. 9(a)) and a $\Delta Load / \Delta strain$ ($\Delta F / \Delta \epsilon$)-step curve (Fig. 9(b)).

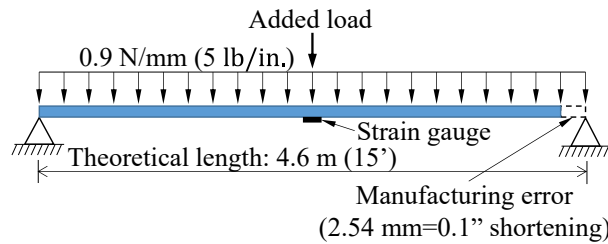


Fig. 8. A beam

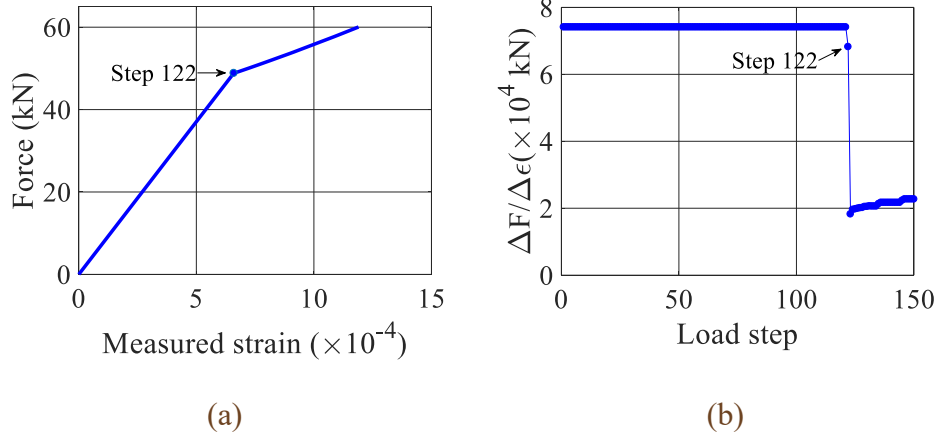


Fig. 9. (a) Load-strain curve; (b) $\Delta F/\Delta \epsilon$ -step curve

From the sudden drop in the $\Delta F/\Delta \epsilon$ -step curve (see Fig. 9(b)), it is identified that the very outmost fiber of midspan of the beam yields at Load Step 122. Associated with this load step, the “ $\epsilon_{m_existing}$ ” is 6.596×10^{-4} , as illustrated in Fig. 9(a). From the yield stress specified in the material manual, the theoretical ϵ_{yield} is calculated as 12.4137×10^{-4} , that is, $\epsilon_{current} = 12.4137 \times 10^{-4}$. By substituting $\epsilon_{m_existing}$ and $\epsilon_{current}$ into Eq. (3), $\epsilon_{unk_existing}$ is obtained as 5.818×10^{-4} . Accordingly, $\sigma_{unk_existing}$ is obtained as 116.328 MPa (16.872 ksi). The identification error is calculated as $(5.829 \times 10^{-4} - 5.818 \times 10^{-4})/5.818 \times 10^{-4} = -0.19\%$, which verifies the effectiveness of the proposed identification approach.

At structural system level

To further validate the proposed approach, this approach is applied to identify the existing stress in a space structural model (called “reticulated Mobius strip”, as shown in Fig. 10) located in the WHAM lab (WHAM, 2017). This interesting reticulated space structure follows the mathematical model of the Mobius strip, which was created by two German mathematicians (August Ferdinand Möbius and Johann Benedict Listing) in 1858. The unique mathematical properties of the Mobius strip exhibit a three-dimensional figure with only one side and one boundary. The Mobius strip has been employed in conveyor belts, such as fan belts and cassette players. As fan belts, the two sides of the belt get the same amount of wear, extending the lifetime of belts; and as continuous-loop recording tapes, they can double the playing time. This reticulated Mobius strip model was designed and manufactured by Geometrica, Inc., which specializes in designing of civil large-scale space structures. It is 3.7 m (12.2 ft.) high, 4.0 m (13.0 ft.) long and 1.0 m (3.4 ft.) wide. It is made of 6061 aluminum, with the Young’s modulus of 71,002 MPa (10,298 ksi), density of 2772 kg/m³ (173 lb/ft.³), Poisson’s ratio of 0.33 and yield strength of 280 MPa (40.6 ksi). All members are tubes with the outer and inner diameters of 25.4 mm (1.0 in.) and 22.2 mm (7/8 in.), respectively. This structure is statically indeterminate.

An experimental test will also be conducted on this structure to implement the proposed approach to identify the existing stress in one member. In order not to damage the rest of the structure, a specially designed weak member will be installed at the location marked in Fig. 10(a). This member will experience yielding much earlier than other members. This way, other members will not be damaged during this test. This member is 0.57 m (1.87 ft.) long and has a rectangular cross section with the thickness of 4.76 mm (3/16 in.) and the width of 12.7 mm (1/2 in.). It is made of A36 steel. The mechanical properties of this steel are the same as the beam example in **Section At member level**. The existing stress will be introduced by a shortening of 2.54 mm (0.1 in.) using turnbuckles, as indicated in Fig. 10(b). Actually, the shortening of 2.54 mm (0.1 in.) introduces a tensile stress of 149.27 MPa (21.65 ksi). In this section, numerical simulation will be conducted first to simulate the process of identifying the existing stress in this member induced by the shortening of the member and the gravity load on the structure.

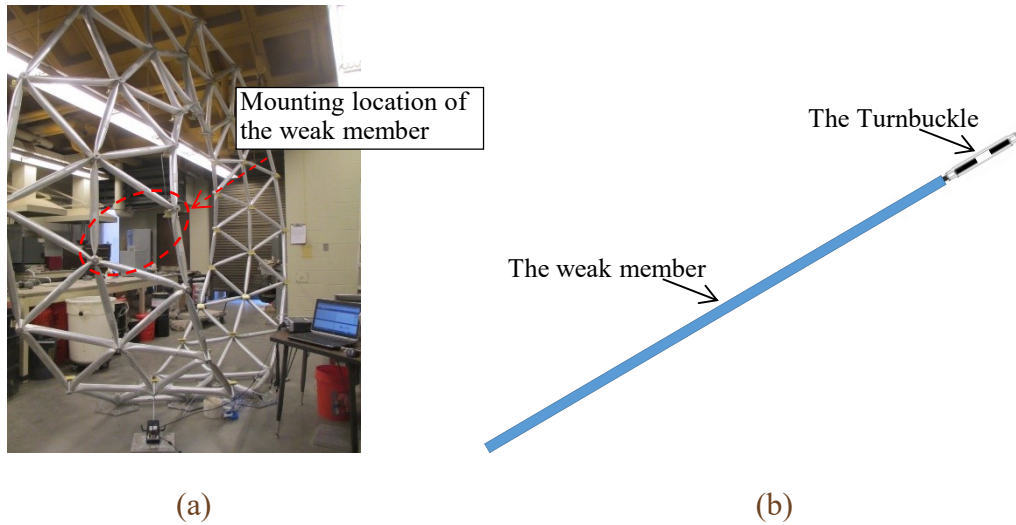


Fig. 10. Reticulated Mobius model in the WHAM lab: (a) Location of the special member, (b) Creating the shortening using turnbuckles

A three-dimensional FE model of the Mobius strip model is established in ABAQUS (Fig. 11). Linear line elements of B31 are adopted, and a coarse mesh is used for the aluminum tubular members while a fine mesh is used for the added steel member. The bottom of the overall structural model is assumed to be fixed.

Through a forward static analysis, the distribution of stresses throughout the system is obtained. The maximum resulting stress and strain occur at the bottom of the steel bar at midspan, which are 149.89 MPa (21.74 ksi, approximately 60% of yield stress) and 7.49×10^{-4} , which are the targets of the identification.

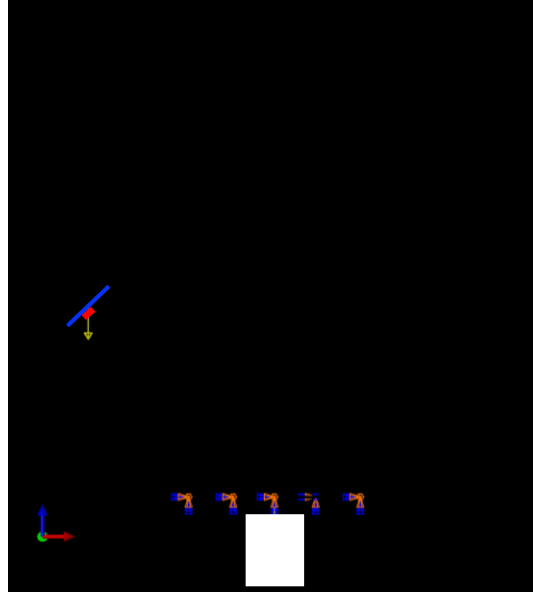


Fig. 11. FE model of the Mobius strip model

The procedure for identifying the existing stress and strain is the same as the beam example. A gradually increasing concentrated load is applied at the midspan of the steel member, and a strain gauge is assumed to be attached to the bottom surface of the steel member at midspan (see Fig. 11). A nonlinear static analysis under the concentrated load is performed, and the load and strain at each load step are saved to construct the load-strain curve (see Fig. 12), and the increments of loading and strain for each step are used to construct the $\Delta F/\Delta \epsilon$ -step curve (see Fig. 13).

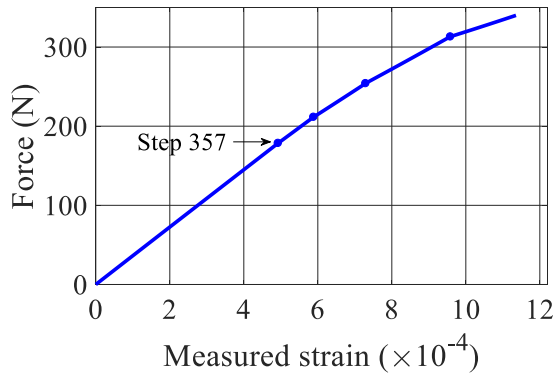


Fig. 12. Load-strain curve

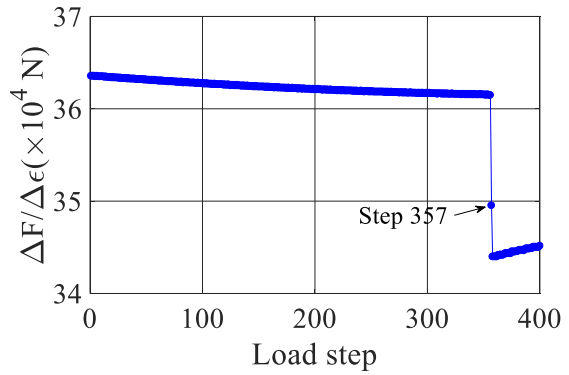


Fig. 13. $\Delta F/\Delta \epsilon$ -step curve

It is shown in Fig. 13 that a sudden drop occurs at Load Step 357, which is identified as the load step when the steel member yields. Then, the strain obtained at Load Step 357 (4.93×10^{-4}) is taken as “ $\epsilon_{m_existing}$ ”. The theoretical ϵ_{yield} ($\epsilon_{current}$) is 12.4137×10^{-4} , which is obtained in the same way as in the beam example. By substituting “ $\epsilon_{m_existing}$ ” and $\epsilon_{current}$ into Eq. (3), $\epsilon_{unk_existing}$ is calculated as 7.49×10^{-4} . Accordingly, $\sigma_{unk_existing}$ is determined as 149.75 MPa (21.72 ksi), which is in

error by -0.1% compared to the target value, 149.89 MPa (21.74 ksi). Once again, it suggests that the proposed identification approach is able to identify the existing stress with a high accuracy.

Experimental Validation

To further validate the proposed approach, a laboratory test has been conducted on the reticulated Mobius strip model in the WHAM lab, as shown in Fig. 10(a). As described in **Section At structural system level**, the existing stress in the steel member with the dimension of 4.76 mm $\times$ 12.7 mm (3/16 in. $\times$ 1/2 in.) will be identified. In the test, the steel member is connected to the Mobius strip model at two ends. At one end, it is rigidly connected to the Mobius strip model. At the other end, it is connected to the Mobius strip model with turnbuckles in order to apply tension, generating the existing stress caused by the shortening resulting from a fabrication error. Weights are applied as the “Added Load” to identify the existing stress. A strain gauge is attached on the bottom surface of the steel member. The test setup is presented in Fig. 14.

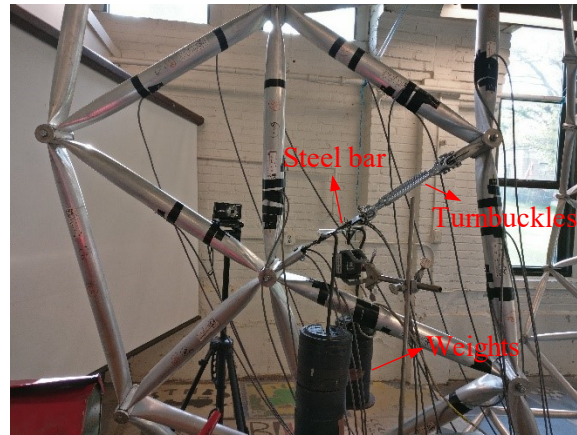


Fig. 14. Test setup of the reticulated Mobius strip model

First, the steel member is elongated by adjusting the turnbuckles to develop an existing strain of 7.6×10^{-4} . The corresponding existing stress is 151.96 MPa (22.04 ksi), which is approximately 60% of the theoretical yield strength of A36 steel. To identify the existing strain (7.6×10^{-4}) and stress (151.96 MPa = 22.04 ksi), weights are gradually applied onto the steel member, and the induced strain at each load step is recorded by the strain gauge. The $\Delta F/\Delta \epsilon$ at each load step is presented in Fig. 15 for the identification of the load step when the member starts to yield.

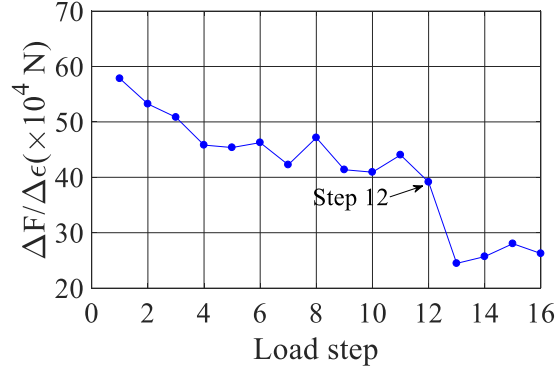


Fig. 15. $\Delta F / \Delta \epsilon$ -step curve based on the test data

To identify the existing strain and stress using the proposed approach, the time instant when the steel member yields is identified from the dropping point in Fig. 15, which is at Load Step 12. Then, the corresponding strain at this load step (4.71×10^{-4}) is taken as “ $\epsilon_{m_existing}$ ”. Consider that the theoretical ϵ_{yield} ($\epsilon_{current}$) is 12.4137×10^{-4} . According to Eq. (3), $\epsilon_{unk_existing}$ is identified as 7.7×10^{-4} . $\sigma_{unk_existing}$ in this member is thus determined as 154.03 MPa (22.34 ksi), which is 1.4% more than the physically developed existing stress (151.96 MPa = 22.04 ksi). From the laboratory test, it is concluded that the proposed identification method is able to accurately identify the existing stress in existing structures.

Conclusions

In this study, a new approach is proposed to identify existing stress in existing civil structures for accurate prediction of structural performance under impending extreme winds. This approach is based on the connection between the unknown existing stress-existing strain curve and the measured stress-strain curve. Two numerical examples are first used to validate the proposed approach; one is at the member level (a beam) and the other is at the structural system level (a reticulated Mobius strip model). Then, a laboratory test on the reticulated Mobius strip model is conducted to further validate the approach. Based on the numerical and experimental results, the following conclusions can be drawn:

- 1) The existing stress can reach a very large magnitude, which is contributed by fabrication error, installation error, the residual stress developed during manufacturing and the stress due to the dead load, live load and other related load effects. When predicting structural performance under impending extreme winds, the existing stress should be considered; otherwise, the stressing condition of structural components will be underestimated.
- 2) Based on the numerical examples, the error of predicting existing stress is less than 0.2%, which demonstrates the effectiveness of the proposed identification approach.

- 3) The results of the laboratory test are in good agreement with the corresponding numerical simulation. The error of predicting existing stress due to shortening is less than 1.5%, which verifies the feasibility and accuracy of the proposed identification approach in a structural system.

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Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

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