Measurement 120 (2018) 34–42

Contents lists available at ScienceDirect

Measurement

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

ESMD-based stability analysis in the progressive collapse of a building model: A case study of a reinforced concrete frame-shear wall model

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A R T I C L E I N F O

Keywords:
Progressive collapse of a building model
Extreme-point symmetric mode decomposition
Time-frequency analysis
Instantaneous frequency

A B S T R A C T

Aiming to estimate the degree of damage influences on a building model, this paper proposes to adopt the extreme-point symmetric mode decomposition (ESMD) method to conduct a stability analysis in the progressive collapse of a building model. As a representative case, a five-story reinforced concrete frame-shear wall building model with a destructible glass wall, is studied in detail. The input signals of key locations on the building model are obtained by high-speed videogrammetry (HSV). First, the original complex response signal is decomposed into a series of simple signals called intrinsic mode functions (IMFs) by a mode symmetric about the maxima and minima points. Second, the instantaneous frequency of each IMF is obtained to perform a stability analysis by a direct interpolation (DI) algorithm. Third, instantaneous energy is obtained to conduct a stress analysis for the key locations of the building model. The results demonstrate that the proposed method has an ability to perform a stability analysis in the progressive collapse of a building model efficiently.

1. Introduction

Structural progressive collapse occurs when a primary structural element fails, resulting in the failure of adjoining structural elements, which in turn causes further structural failures [1]. Structural progressive collapse inevitably leads to a large number of serious loss of lives and property, which has a negative social impact [2,3]. Therefore, aiming to avoid structural progressive collapse, before building a structure, a corresponding building model of a certain scale should be constructed to carry out progressive collapse experiments, with the goal of acquiring the dynamic response signals of key locations by a sudden removal of the primary structural components. Stability analysis from the dynamic response signals has become one of the most interesting research topics in structural health monitoring (SHM) area, and it can be used to estimate the degree of damage influences on a building model [4,5].

In general, a building model may exhibit time-varying system properties under the sudden removal of primary structural components. It is important to track these properties for structural stability analysis based on the acquired non-stationary dynamic response signals [6]. At present, the most commonly used method for structural stability analysis is time-frequency analysis (TFA), by which vibration-based non-stationary dynamic response signals are analyzed [7]. The fast Fourier transform (FFT) was the first TFA method for structural stability analysis, and it has been used in various types of building models [8]. However, FFT has two significant limitations. It cannot depict changes in vibration-based frequency signal content over time, and it cannot be used to monitor real structures subjected to dynamic excitations [9]. To overcome the limitations of FFT, a short-time Fourier transform (STFT) was produced for structural stability analysis by analyzing non-stationary or noisy signals [10]. The basic idea of STFT is to divide the initial response signal into small time windows and represent variations in signal frequency content over time by Fourier transforms of these time segments [11]. However, there is a tradeoff between the size of a time window and the frequency resolution, which cannot adequately represent the dynamic transient behavior of the structure [12]. A wavelet transform (WT) represents a family of elementary functions by wavelets, which can be dilated and shifted independently. Wavelets are localized in both time and frequency [13]. WT has great potential to detect sudden changes from dynamic response signals, and it has been applied in the field of structural stability analysis [14,15]. However, WT is still an adaptive-window Fourier method based on the principle of linear superposition. It can handle nonstationary signals only for linear systems by a priori knowledge, and also is limited by the size of

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https://doi.org/10.1016/j.measurement.2018.01.038
Received 20 July 2017; Received in revised form 22 December 2017; Accepted 23 January 2018
Available online 07 February 2018
0263-2241/

the mother wavelet [16]. In conclusion, it is difficult for traditional Fourier-based methods, such as STFT and WT, to process nonstationary and nonlinear signals, such as the dynamic response signals acquired from the progressive collapse of a building model in this study.

Aiming to extract the properties of nonstationary and transient signals, Huang et al. proposed the Hilbert–Huang transform (HHT) as an adaptive signal-processing technique with the capacity to analyze nonlinear or nonstationary signals [16]. HHT consists of the two key steps of empirical mode decomposition (EMD) method and Hilbert spectral analysis. The EMD method decomposes any complicated time-series data into a collection of band-limited quasi-stationary functions called intrinsic mode functions (IMFs). Hilbert spectral analysis yields meaningful instantaneous amplitude and frequency information from nonlinear or nonstationary signals for each IMF [17]. With the advantage of requiring neither an a priori primary-function nor a preset window-length, HHT has been applied to vibration signal analysis in different fields, such as mechanical, biomedical, and earthquake engineering [18,19]. However, HHT has some shortcomings when used for structural stability analysis. First, the sifting time is difficult to determine and the decomposed trend functions are too rough. Second, as the unenviable IMFs, it may bring about misinterpretations of results in low frequency regions. Third, Hilbert spectrum analysis is limited regarding the energy as a constant to be mapped into a series of fixed frequency.

Recently, an innovative algorithm, extreme-point symmetric mode decomposition (ESMD), has been proposed for TFA [20]. Rather than constructing two outer envelopes for the sifting process of HHT by a least-square method, ESMD is implemented by an optimal global mean curve interpolated by the midpoints of the line segments connecting the local maxima and minima points. This will reduce the difficulty in determining the optimal sifting time. ESMD shows considerable potential in the areas of information science, marine and atmospheric sciences, economics and seismology [21–23].

Therefore, on the basis of three-dimensional (3D) time-series data acquired by high-speed videogrammetry (HSV) method introduced in Liu et al. [3], this paper further extends to adopt the ESMD method to conduct a stability analysis in the progressive collapse of a building model. The rest of this paper is organized as follows. The building model is introduced in Section 2. Section 3 introduces the stability analysis method. Section 4 describes the experimental results and analysis, followed by our conclusion in Section 5.

2. Building model

In the study, a building model is a five-story reinforced concrete frame-shear wall with a destructible glass wall at the bottom. Fig. 1 demonstrates a photo of the building model taken by a camera. The purpose of the experiment is to obtain the dynamic response signals of key locations on the building model by the sudden loss of the destructible glass wall, and to conduct a stability analysis of the progressive collapse of the building model. Fine aggregate concretes and galvanized iron wires are used to construct the building model. The glass wall is made from a kind of organic glass, with compressive strength of 28 N/mm^2 and thickness of 5 mm. The floor live load is 2.0 kN/m^2, and the size of the building model can be seen in Fig. 1.

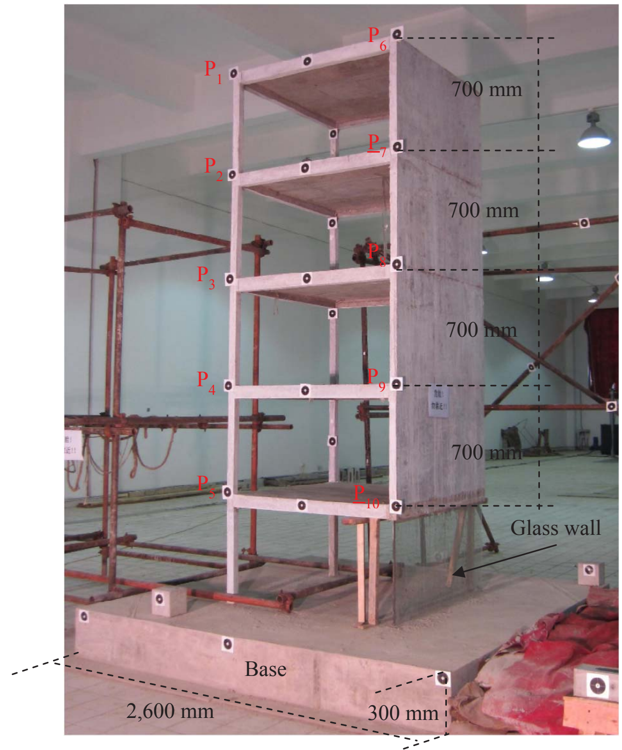

Fig. 1. A photo of the building model taken by a camera.

3. Stability analysis method

3.1. Signal decomposition

Any one complicated response signal can generally be regarded as being composed of multiple simple signals with their own inherent natural frequency [24]. The purpose of signal decomposition is to decompose the original response signal into a series of simple signals, and further seek the main sub-signal of the original response signal. The acquired response signal of the progressive collapse of the building model in this study is nonlinear. Therefore, ESMD is proposed to decompose the original response signal into a series of finite and small IMFs together with an optimal adaptive global mean (AGM) curve, which can determine the corresponding meaningful instantaneous frequency of each IMF. The signal-decomposition procedure for a given complicated response signal $s(t)$ is shown in Fig. 2.

Step 1: Midpoint seeking.

Find all the local maxima and minima points of the response signal $s(t)$ and enumerate them as $E_i(i = 1,2,\cdots n)$. Connect all the adjacent extreme points E_i with line segments and enumerate their midpoints as $M_i(i = 1,2,\cdots n{-}1)$.

Step 2: Boundary processing.

The purpose of boundary processing is to determine boundary

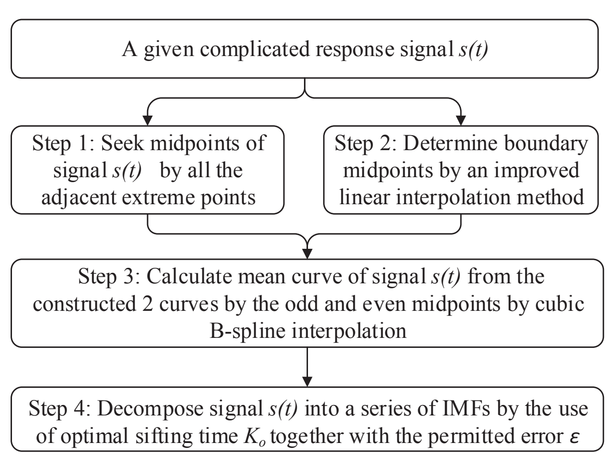

Fig. 2. Flowchart of signal decomposition by the ESMD method.