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Automated Measurement of the Deformation of Damaged CBF Structures with Images

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Abstract: In the aftermath of earthquake, mobilizing post-earthquake reconainssance teams is a tedious process and frequently it takes days to complete building inspections in order to assess the level of damage. According to the detailed evaluation assessment form of ATC-20 procedure (1989, 1995), inspectors need to investigate the post-earthquake safety of buildings based on the following damage criteria: overall, structural, non-structural and geotechnical hazards, while relying on their engineering judgement and experience. To reduce the duration of the traditional evaluation process, in this paper, a novel method which consists of automatically capturing the nonlinear deflected shape of structural members is proposed and developed for concentrically braced frames applications. The proposed method employs image processing techniques. First, all critical connecting points of the geometry of a concentrically braced frame structure are identified. Then, based on the relative positions of the connecting points, the corresponding structural members such as: columns, beams, braces and connections can be recognized. In the following step, the configuration of these permanent deformed structural members symbolised by their center-line is compared with their original center-line configuration. Thus, by applying the proposed method, the permanent deformation of each structural member is estimated and based on the computed fragility curves, the level of damage is assessed, while the building is classified as reparable or irreparable. In this paper, the application is conducted on a chevron-bracing system of a two-storey office building located in Victoria, BC.

1 Introduction

Steel structures designed according to the current practice are expected to meet the required performance objective under seismic loading. Thus, all residential, commercial or industrial structural systems should perform as earthquake-resistant buildings, implying that all columns belonging to the gravity and seismic force resisting systems, beams, horizontal diaphragm and connections must remain undamaged, while sustaining the inelastic response of brace members, proportioned to dissipate the input energy. In term of earthquake risk, the existing building stock, designed and built prior to the implementation of seismic design requirements in the Canadian code (1970) is much larger than the earthquake-designed building stock and is likely to exhibit non-structural and/or structural damage during a moderate to severe earthquake.

According to the detailed evaluation assessment form of ATC-20 procedure (1989, 1995), inspectors need to investigate the post-earthquake safety of existing building stock based on the following damage criteria: overall, structural, non-structural and geotechnical hazards. In this light, overall hazards consist of partial or global collapse failure that usually occurs due to storey-mechanism when excessive drift is concentrated within a floor. The structural hazards is defined when columns, horizontal diaphragms, vertical bracing systems, connections or foundations undergo minor, moderate or severe damage and the non-structural hazards is identified when failure of parapets, ceiling, cladding, partition walls, elevators, stairs cases, light fixtures or piping supports undergo total or partial failure. In addition, geotechnical hazards deal with slop failure, sliding or soil liquefaction.

In the aftermath of earthquake, it takes days to complete the building inspections. Thus, according to the summary report released after the occurance of 6.3 magnitude Christchurch earthquake (February 22, 2011), Lizundia (2012) noted that 72882 hauses were investigated in ten days. This seismic event was the aftershock of the 7.1 magnitude earthquake that rocked the same area on September 4, 2010. Since the occurrence of the mainshock, the Christchurch region experienced several aftershocks of large magnitude and the process of building inspectiction was repeated at least three times between September 2010 and June 2011, when the third 6.3 magnitude aftershock occurred in the same damaged area. The particularity of Christchurch earthquake was the larger number of aftershocks of large magnitude.

Considering the importance of post-earthquake building inspections and the requirements of fast operation time, several efforts have been made towards the development of automating building safety assessment (Zhu et al., 2011). In general, field inspectors relay on engineering judgement and experience when investigating the damage level of building structures. Searching for hidden damage such as beam-to-column or brace-to-frame connections may be very expensive and disruptive, while impairing the overall building capacity or the safety of adjacent constructuctions. For example, integrating computational processes with embedded sensors and actuators installed in new buildings can provide useful information in evaluating structural damage (Kottapalli et al., 2003). In addition, by using a similar technique, the dynamic characteristics of an undamaged or damaged steel building may be evaluated (Prolux et al., 2012). However, the number of buildings with installed sensor networks is limited in seismic areas and rarely may be encountered in existing vulnerable steel buildings.

To reduce the duration of traditional evaluation process of damaged structures, in this paper, a novel method which consists of automatically capturing the nonlinear deflected shape of structural members is proposed and developed for concentrically braced frames applications, CBFs. The proposed method employs the image processing techniques. First, all critical connecting points of the CBF's geometry are identified. Then, based on the relative positions of the connecting points, the corresponding structural members such as: columns, beams, braces and connections can be recognized. In the following step, the configurations of these permanent deformed structural members are compared with their original configurations. Thus, by applying the proposed method, the permanent deformation of each structural member is estimated. In the following step, by employing fragility functions developed according to FEMA P695 (2009), the level of structural damage is assessed and the building is classified as reparable or irreparable. In this paper, the selected application is a two-storey CBF office building in chevron-bracing configuration, located in Victoria, BC. To validate the effectiveness of the proposed method, the processed deformation measurements of the CBF system that was subjected to crustal ground motions are tested against the results obtained from nonlinear time-history analysis.

2 Background

Earthquake-resistant building structures are designed to perform safety when subjected to scaled ground motions at the design level. However, after the occurrence of the mainshock, the vulnerability of buildings to aftershocks is not addressed in specifications and needs to be assessed in a short delay because the vulnerability to damage of affected buildings is high. Thus, to accurately quantify the risk of buildings to collapse is of critical importance and may be done by linking the visually identified damage of structural and non-structural members to building performance models.

According to Reveilleere et al. (2012), after a mainshock, the assessment of building stability can be achieved based on the following techniques:

- Inspection-based relaying on engineering judgement;

- Shake-maps of the affected area, developed based on the event magnitude and location (uncertain hazard);
- Instrumentation through hazard level estimation based on analysing recorded ground motions. For post-disaster building structures it is recommended to perform instrumentation for monitoring the reduction of stiffness and lateral deformations.

The main part of the required analytical procedure is to find a relationship between engineering demand parameters (e.g. interstorey drift) and damage parameters (e.g. 5%-damped spectral response acceleration corresponding to the main period of the structure and expressed as a ratio to gravitational acceleration). Distribution of interstorey drift and the residual drift across the structure height needs to be computed for each identified damage state leading towards collapse. Brace members of the CBF system are proportioned to yield in tension and buckle in compression. After buckling of braces occurred, these possess only the post-buckling strength and the unbalanced force developed at the location of brace-to-beam connection may produce hinging of the beam while columns must be proportioned to support the axial force developed in braces. In general, under earthquake loading, braces of CBFs usually deflect out-of-plane. According to FEMA P695, safety of building structure is expressed in terms of collapse margin ratio which is defined as the ratio of the median 5%-damped spectral acceleration of the collapse level ground motions to the 5%-damped spectral acceleration ground motions at the fundamental period of the earthquake-resistant structure. The 5%-damped spectral response acceleration values for the reference ground conditions are based on a 2% probability of exceedance in 50 years (NBC, 2010). The collapse fragility curve that quantifies the probability of collapse includes the variability of ground motions and uncertainity in design, analysis, and construction. An example of building fragility curves for existing CBFs building structures may be found in literature (Tirca et al., 2013). In general braces of CBFs are made of hollow structural sections, while beams and columns are made of W-shape.

Linking the observed damage to fragility curves that are built for different performance levels is a critical component of the assessment method. From visual observation, the floor level where damage is concentrated could be identified, as well as the initiation of plastic hinges in the structural members. A different texture of steel material may signify yielding of material due to the plastic hinge formation. By identifying material changing, additional effort into the model-building process is introduced. Columns of braced frames, as well as gravity columns need to remain undamaged during the mainshock. When buckling of columns occurs, the system's stiffness degrades, while building's stability is at risk. Linking damage observations with fragility curves developed for groups of components such as: braces; brace-to-frame connections; beams of CBFs; columns of CBFs; shear connections between beams and columns of CBFs; gravity columns; horizontal diaphragms and non-structural components (e.g. building's facade) are critical steps in the assessment process. According to ATC-58 (2011), for fragility calculation, four procedures are presented based on the type of associated limit state to damage such as: i) strength-limited damage states; ii) ductility-limited damage states; iii) displacement-limited damage state and iv) code-based limit state.

Regarding the risk assessment procedure, the NBC 2010 and Quebec Building code (2010) does not require action when the existing structure is able to carry at least 60% of the design base shear. Meanwhile, the California Building code (2010) requires action when "substantial" damage has occurred. Herein, "substantial" damage means: a reduction of more than 20% of the seismic force resistant system capacity and/or vertical gravity load-carrying capacity of columns that support more than 30% of floor area. When CBF's members and their connections exhibit "substantial" damage, the retrofit action towards seismic upgrading should be considered when the system capacity dropped below the 75% of code demand, while for gravity columns, returning to the 100% strength capacity is required.

3 Proposed Methodology

The main objective of this paper is to investigate whether the deformation of damaged CBF structures can be measured in an automatic, accurate, and faster manner. In order to achieve this objective, a novel method for measuring the deformation of damaged CBF structures based on image processing techniques is proposed. In this method, all critical connecting points and end points of the CBF geometric shape are first identified using the corner detection. Then, the topological configuration of the CBF geometric shape is retrieved by linking the detected critical points. The topological configuration and the detected critical points characterize the deformation of the damaged CBF shape structure. In this way, the structure's deformation can be estimated with little human intervention. The overall framework of the proposed method is illustrated in Figure 1 and details are given below.

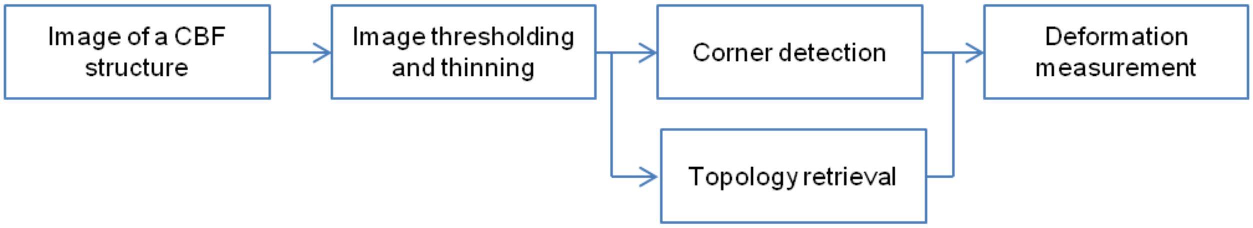


Figure 1. Framework of the proposed methodology.

3.1 Critical Points Identification

The first step in the proposed method is to identify the critical points in the skeleton of the CBF shape that can be achieved through the image thresholding and thinning (Cychosz 1994). The critical points in the skeleton are those points that have connecting functions or are at the end positions (Figure 2). In order to identify these critical points, the Shi-Tomasi corner detector (Shi and Tomasi 1994) is first adopted to locate the points of interest when there is a large intensity variation in the perpendicular directions (Cooke and Wshatmough, 2005). Then, the detector is based on the Harris corner detector (Harris and Stephens, 1988) with one slight modification applied to the corner “selection criteria”. Not all points of interest located by the Shi-Tomasi corner detector (Shi and Tomasi, 1994) are the critical points. Therefore, further checking of these points is required. To proceed, a local window (7x7 image pixels) is placed on each point of interest and the skeleton found in the window is extracted. The point is considered to be a critical point when it meets one of the following two conditions: 1) there are more than two skeleton segments connecting to the point in the local window; or 2) the overall skeleton segment passing through the point does not cross over the window from one side to another in *x*- or *y*- direction.

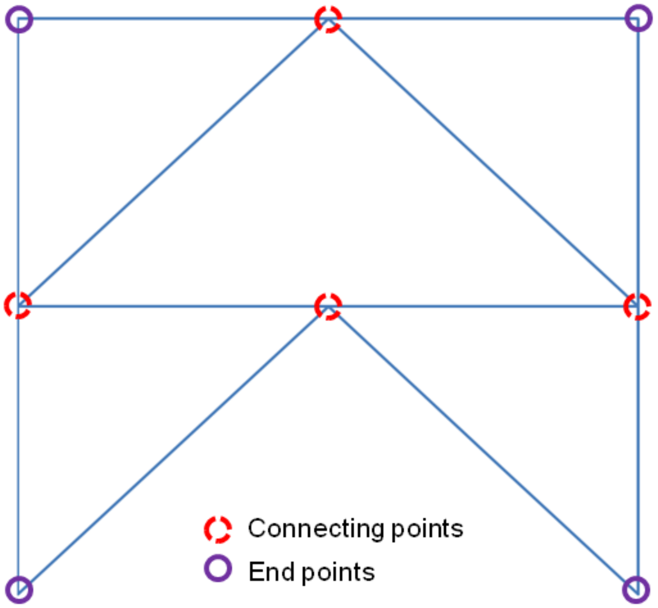


Figure 2. Connecting end points in the CBF structural system.

3.2 Topological Configuration Retrieval

When the critical points are identified, the topological configuration of the CBF shape structure can be retrieved. A straightforward way is to link two critical points as long as they are directly connected in the skeleton. However, checking the skeleton connectivity by analysing all points is time-consuming, especially when the geometrical shape of the structural frame has a high level of complexity. In addition, the potential errors in estimating the critical points may fail the connectivity checking procedure. Considering these issues, a new procedure has been proposed here to retrieve the skeleton topological configuration instead of checking the connectivity between the critical points.

Specifically, the procedure consists of two main steps. First, for any two critical points, it is assumed that there is a line segment connecting these two points. The line segment is morphologically 'dilated', and combined with the structure skeleton using the logic operation, 'and'. If the results after the combination contain a skeleton segment, it means that the assumption made before is valid and the line segment should be kept. Otherwise, the line segment must be discarded accordingly. In this way, all potential line segments that connect the critical points can be identified and the line segments pool is formed.

When the pool for the line segments is created, any three line segments in the pool that can be used to form a triangle are checked. For each triangle, if the length of its longest side is almost the same as the sum of the length of the other two, it means that the line segment representing the longest triangle side can be replaced by the other two in the CBF geometry. Therefore, this line segment is removed from the pool. After checking all possible triangles, the line segments remaining in the pool construct the topological configuration of the CBF system.

4 Implementation and Results

4.1 Implementation

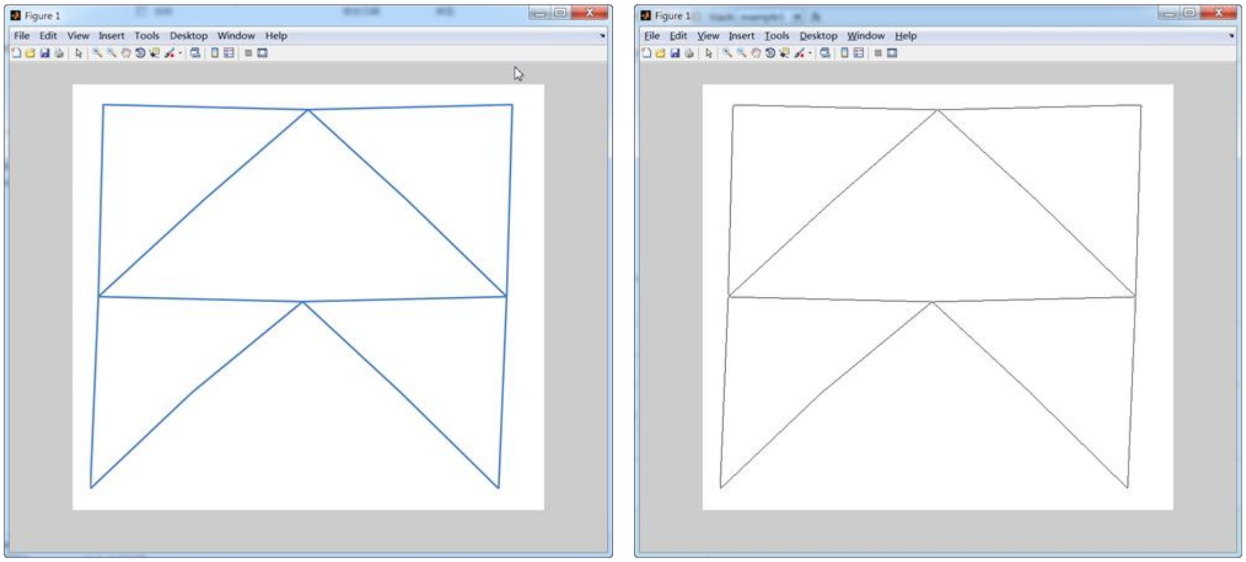
The proposed method has been implemented with Matlab R2012a. The Matlab provides the toolboxes for image processing, computer vision, image acquisition, etc. (Mathworks, 2012), which are necessary for the method implementation. Figure 3 shows the screenshots of using the proposed method: 1) loading the deformed shape of the CBF system; 2) generating the skeleton of the CBF system; 3) identifying the critical points of the CBF system; and 4) retrieving the topological configuration of the CBF system geometry. The critical points and topological configuration are highlighted with red color in the figure.

4.2 Results

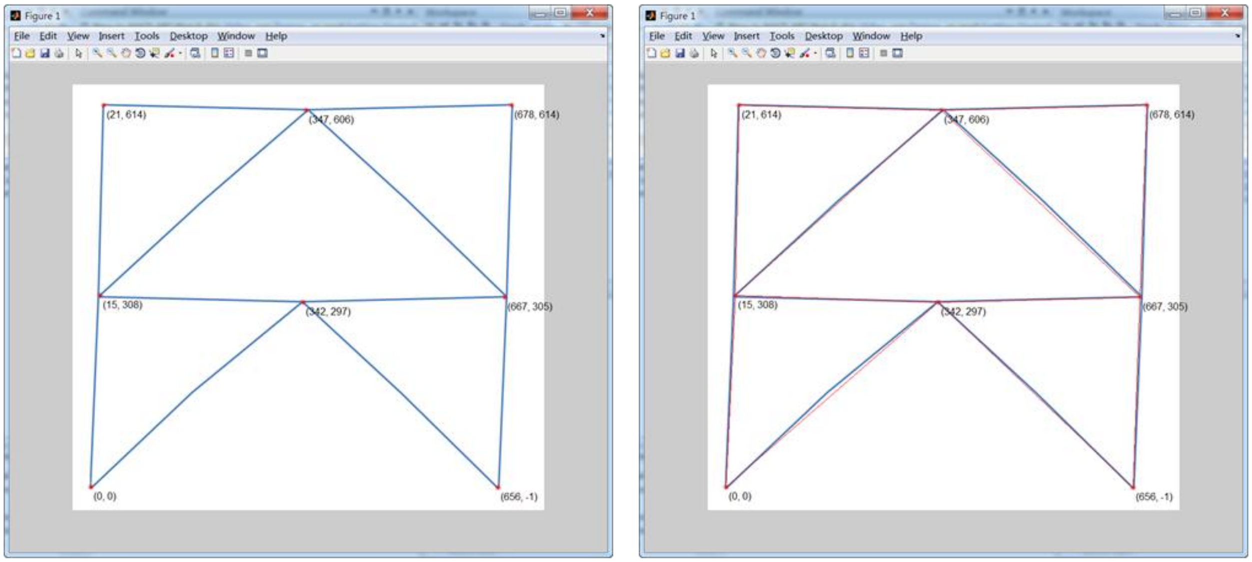
In order to measure the accuracy of the identified critical points, all points coordinates calculated from the method are compared with those computed analytically. For the 2-storey CBF, the coordinates of the critical points calculated from the method and those computed based on manual identification are given in Table 1. Thus, the absolute error of each critical point is estimated. According to data given in Table 1, the average absolute error of critical points identification as resulted from the method reach 1.63 pixels in *x*-direction and 3.88 pixels in *y*-direction.

4.3 Loss estimation

In the aftermath of earthquake, performing fast and accurate estimation of losses is critical. For most buildings and especially for those located in low to moderate earthquake areas, the cost of repairing non-structural elements greatly exceeds that for structural damage (Zhu et al., 2011). However, the cost of economic losses can be significantly higher when the cost of lost productivity during the required time for building’s retrofit is included. The cost and time for the seismic upgrading and damage reparation of CBF buildings may be estimated by using the retrofit fragility functions. In this respect, a framework for loss estimation, developed on the basis of demanded retrofit work, is given in the volume of ATC-58 (2011).



(a) Image loading (b) Skeleton generation



(c) Critical points identification (d) Topological configuration retrieval

Figure 3: Screenshots of using the proposed method.

Table 1: Coordinates of critical points

No.	Proposed Method		Manual Identification		Difference	
	X (Pixel)	Y (Pixel)	X (Pixel)	Y(Pixel)	|dX|	|dY|
1	667	305	669	309	2	4
2	656	-1	657	-2	1	1
3	342	287	341	298	1	12
4	347	606	350	607	3	1
5	0	0	-1	-2	1	2
6	15	308	13	306	2	2
7	21	624	20	615	1	9
8	678	614	679	614	2	0

Note: the left-bottom point of the structure is set as the original point of the coordinate system.

5. Conclusions

In the aftermath of earthquake, mobilizing post-earthquake reconainssance teams is a tedious process and frequently it takes days to complete building inspections. According to the detailed post-earthquake evaluation assessment form given in the ATC-20 volume (1989, 1995), inspectors need to investigate the building stock based on the following damage criteria: overall, structural, non-structural and geotechnical hazards, while relying on engineering judgement and experience that may be subjective.

To reduce the duration of the traditional evaluation process of damaged buildings, in this paper, a novel method which consists of automatically capturing the nonlinear deflected shape of structural members is proposed and developed for concentrically braced frames applications. The proposed method employs the image processing techniques. First, all critical connecting points of the CBF geometrical shape are identified. Then, based on the relative positions of connecting points, the corresponding structural members such as: columns, beams, braces and connections are recognized. In the following step, the configuration of these permanent deformed structural members symbolised by their central-line is compared with their original central-line configuration. Thus, by applying the proposed method, the permanent deformation of each structural member is estimated and based on the computed fragility curves, the level of damage may be assessed. As a final objective, the proposed framework is expected to provide the quantitative damage level, as well as the vulnerability to aftershocks of CBFs building structures.

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