CFSRC
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Proceedings of the Cold-Formed Steel Research Consortium Colloquium
17-19 October, 2022 (cfsrc.org)

A stochastic imperfection simulation method from high-fidelity measurements on cold-formed steel studs

Xiao-yan Sun[1], Haohao Peng[1], Xi Zhao[2]

Abstract

This paper presents a stochastic imperfection simulation method towards cold-formed steel (CFS) studs, the data of which is generated from a high-thruput laser measurement device. An accurate hand-held laser scanner is applied to investigate about 19 types of CFS studs that widely used in current Chinese markets. point cloud models of which are reconstructed. A developed imperfection pattern recognition algorithm efficiently processes the high-fidelity point cloud models and automatically characterizes the imperfections based on the local, distortional, and global buckling modes. The measured imperfection data is statistically analyzed, where statistical models and inter-correlation models of mode imperfections are carefully obtained thereafter. The inter-correlation matrices and statistical models are parametrized for stochastic analysis. A data-driven stochastic imperfection simulation method thus is proposed based on the as-real correlation parameters and statistical data. The generated imperfection models are compared with the measured imperfections to validate the proposed simulation method. The investigation provides consolidated data foundations for the imperfection sensitivity analysis. The evaluation of CFS studs’ reliability can be insightfully conducted; thus, the imperfection design in the general specification is advised. The proposed imperfection simulation method based on inter-correlation parameters and as-measured statistical models also contributes to the development of trending simulation-based design of cold-formed steel structures.

1. Introduction

It is well known that cold-formed steel members are susceptible to interference from many factors in the process of stressing due to their large slenderness ratio. Among them, geometric imperfections exist in every life cycle of cold-formed steel members, and their appearance complicates the mechanical properties of cold-formed steel members. Therefore, considering geometric imperfections when exploring the simulation of finite element collapse of cold-formed steel has become the focus of scholars. However, due to the randomness of the appearance of imperfection forms (actual and nominal material properties [1], actual and nominal geometry [2-3]), the load-bearing capacity is affected not only by material nonlinearity, but also by geometric nonlinearity. In the design of light steel structures, ideal geometric dimensions are usually adopted to ignore the impact on the geometric imperfections of components, which will undoubtedly lead to structural safety hazards.

Therefore, it is important to try to measure the geometric deviation between the actual member or structure and the ideal structure and to accurately characterize the geometric imperfections of the member, and to choose an appropriate simulation method to simulate such imperfections in order to deal with realistic problems in structural design.

At present, most of the commonly used methods to quantify geometric imperfections still use straightedges, micrometers, and other contact measurement methods, which not only consumes time and effort, but also collects geometric data to be rough and cannot effectively and completely characterize geometric imperfection information. Therefore, the imperfection measurement method at this stage has gradually developed from traditional contact measurement to high-precision optical measurement technology. The more commonly used methods are photogrammetry [4] and laser measurement [5-8]. Based on the obtained point cloud data, the three-dimensional geometric information of the target object can be accurately and efficiently characterized for experimental analysis and simulation modeling. In particular, the photographic technique uses a device that captures images of the member to capture the target and then processes the images to generate a three-dimensioned point cloud that can be used for dimensional point that can be used to study the geometric imperfections of cold-formed

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[1] Graduate Student, School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, P.R.China;

[2] Associate Professor, School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, P.R.China;

steel members. Burcu[9], Korumaz[10], Selvaraj[5], Zhu[11] et al. have also carried out research on cold-formed C-beam, I-beam and other cross-shaped steel components based on laser measurement and three-dimensional laser scanner technology, and reconstructed the real Three-dimensional geometry to obtain the initial geometric imperfections of the component. Considering that it is difficult to capture the detailed angles such as corners and thickness of cold-formed steel members, the handheld laser measurement instrument, which can move in all directions, is more advantageous than the camera measurement technology, which is prone to image distortion and has less measurement data. However, the existing laser scanning technology still has great progress in the research of imperfections. Due to the large amount of data, the difficulty of extracting geometric imperfections has greatly increased. How to extract key geometric imperfections from a large number of component geometric point clouds that have an impact on the carrying capacity of components needs to be further explored.

Second, in order to predict the nonlinear behavior of members, numerical simulations and physical tests have become two of the more common means to study the buckling analysis of cold-formed steel members. In reality, the initial geometric imperfections of the members have a random nature independent of the geometry and geometric properties [4], and the law is difficult to summarize. Most of the data values used for strength prediction in existing studies are based on the imperfection magnitudes specified in the code, making the existing imperfection modal simulation method unable to predict the real random geometric imperfections [5]. Moreover, geometric imperfections have a more complex form of three-dimensional spatial variation, but there is no consensus on modeling their complete three-dimensional spatial patterns [6]. Based on this, it is necessary to simulate with the actual measured imperfections according to the geometric nature of the member to reach the strength prediction of the member under the distribution law of the initial imperfections of the real cold-formed steel.

Based on the above, cold-formed C-shaped steel members are studied as the research object, and the geometric imperfections of cold-formed steel members are studied. In this paper, Dual blue light handheld 3D scanner is used to scan cold-formed steel members with high precision. Based on all-round data collection, a point cloud processing algorithm is compiled to complete the extraction of geometric characteristics and geometric imperfections of profile steel members. Through experiments and numerical simulations, the impact of measured geometric imperfections on the buckling mode of cold-formed steel members is verified, and provides ideas for further improving the accuracy of strength prediction.

2. Imperfection measurement scheme and data processing

2.1 Specimen selection

The test subjects used cold-formed C-shaped steel components, and a total of three cross-section sizes were selected. The thickness of the nominal steel ranged from 2mm to 3mm, the standard web height was from 180mm to 280m, and the widths of the winding and flange were uniformly specified as 20mm and 70mm. The length of the component removes the clamping part of the fixture, and the calculated length is 250mm (short column), 1000mm (medium column) and 2800mm (long column). The selection principle is based on the length of the component, local buckling, distortion buckling and overall buckling mode. This process is realized with the help of CUFSM.

2.2 Laser scanning for acquire of geometric information

Data acquisition is based on the portable handheld 3D scanner (Figure 1). The working principle is that the laser 3D scanner projects specific light on the scanning target component, and then the device camera receives the light reflected back from the target component. With the help of the triangulation method, the position of the key point is calculated. Marker, through the position of the point, the composition of the point, and the line composition surface, so as to convert the entity outline of the scanner into three-dimensional data composed of point cloud data. The laser scanner has two light sources: LED light source and blue laser light source. Among them, LED structured light can obtain data efficiently and quickly, while the laser light source takes into account the capture of the details of the scanning accuracy. Its accuracy can reach 0.04mm and the minimum point spacing is 0.05mm.

Figure 1: Laser Scanner

In order to scan the overall profile steel members in an all-round way, the molded steel members are placed on four brackets of equal length. Because the geometric shape of cold-formed steel members is relatively regular, in order to successfully obtain three-dimensional data, it is necessary to carry out enough paste-assisted identification of markers. Then the error correction of the scanner (this error is 0.04mm), and then the scanning work can be carried out. During work, in order to ensure that the scanning work can be carried out normally and the quality of scanning data, it is necessary to always correct the distance range limit of the scanner when operating the scanner equipment. After obtaining the initial point cloud of the component, the scanning cross-section can eliminate the environmental noise outside the component through the connected domain function. This operation will not destroy the original geometric characteristics of the data, and then use the post-processing function and measurement module to repair, smooth and sharpen the scanned data. The complete point cloud data diagram of the target object (Figure 2) can be obtained as a three-dimensional entity reconstructed based on scanning point cloud data.

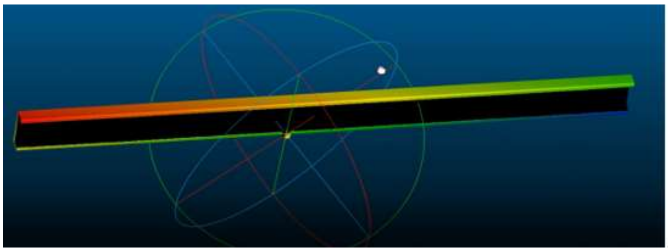


Figure 2: 3D solid formed by point cloud data

2.3 *Imperfection definition*

Geometric imperfection characterization plays an important role in the simulation of random geometric imperfections of cold-formed steel members. The initial geometric imperfection is usually defined as the measured geometric deviation between the ideal component. Common geometric imperfections are divided into three global imperfections: bending, twisting and torsion, as shown in the Figure 3.As well as two cross-sectional imperfections: local imperfections and distortion imperfections.

Among the existing imperfection characterization methods, whether the traditional imperfection characterization method or the MID modal decomposition method, there are unified rules for the representation of overall imperfections: that is bending and distortion measure the two imperfections by comparing the deviation distance between the center of the cross-section and the perfect model. The torsion imperfection is characterized by comparing the angle offset size of the web. This paper mainly discusses the extraction of global imperfections.

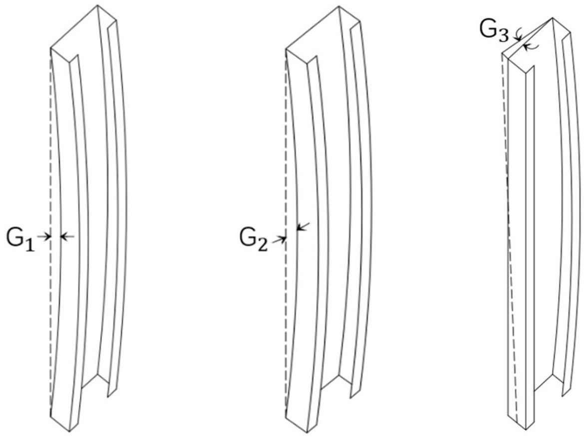


Figure 3: Three overall imperfection

2.4 *Imperfection extraction*

2.4.1 *Point cloud data processing*

Encapsulated data storage often leads to disordered point clouds, so algorithms are written first to sort out-of-order point clouds. Point cloud information includes three-dimensional coordinates (xyz) and direction angle information, then import it into the algorithm, uses principal component analysis (PCA) to determine the main coordinate axis of point cloud data and uses the least square method to determine the three-dimensional line of point cloud and the orthogonal vector creates the coordinate system of the most suitable member. In this study, the coordinate axis along the length of the member is defined as the main coordinate axis x. The axis along the horizontal direction of the web in the cross-section is the y-axis, and the direction along the longitudinal axis of the flange is the z-axis.(Figure 4). The second step is data processing: First of all, evenly divide the voxel according to the shape size of the component, traverse the point cloud data, mark the voxel block where the point cloud point is located, and store the point cloud coordinate index. Then slice the member along the long axis of the member, judge the opening direction of the image, and evenly divide the section into left and right areas along the central axis. Sort the point cloud points in the left and right regions separately. Find the center point of the cross-section, define the reverse direction of the opening direction as the initial direction, and calculate the angle between each point and the initial direction in turn. Sort it in ascending order according to the angle to get the point cloud order of this area. However, the point cloud at the edge position may be out of order. At this time, the point cloud order of the edge part is corrected by selecting the point cloud coordinates of the edge part and sorting by the straight line distance from the center point. Finally, the point cloud sequence of the left and right regions is spliced to obtain the point cloud order of all this cross-section.(Figure 5) Repeat the above steps to sort the point clouds on each slice of the member, and store the point cloud coordinates of all sections in order.

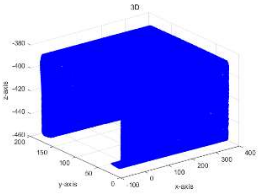


Figure 4：Point cloud data for conversion directions

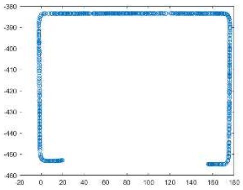


Figure 5：Sorted completed point cloud data

2.4.2 *Feature recognition*

The geometric characteristic parameters such as slope, truncation, radius, etc. of the curve function of the web, flange, lip and corner are extracted from the complete point cloud data sorted. These parameters can be used as reference data for positioning components and random modeling in the next step. In order to facilitate feature extraction, the geometric point cloud model of cold-formed C-shaped steel members is highly parameterized, and decomposed into global modes controlled by 3 parameters and local modes controlled by 22 parameters, and its point coordinates are converted into parameters that can be expressed by mathematical formulas. Geometric parameters can be used to describe the geometric characteristic information of profile steel members. Based on this, a feature recognition algorithm based on robust optimization is proposed to automatically locate the boundary points of different geometric features and decompose the cross-section into the area. In order to further optimize the algorithm, firstly is to fit linear curves and arc curves to the plane and angular regions to filter noise. Secondly, an iterative function is used to minimize the error between the fitted and measured points. In this way the effect of uncertainty in the cross-section of the real member is considered. Therefore, the geometric features are optimally obtained, followed by an in-depth analysis of the cold formed steel members.

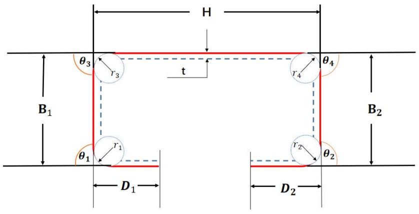


Figure 6：Geometric feature extraction

2.4.3 *Imperfection extraction*

The calculation of global imperfections mainly depends on the center positioning of components. Considering that the cold-formed C-shaped steel member is not necessarily a perfect C-shaped when the component leaves the factory, an algorithm is written to redefine the geometric relationship of each special point so that it can be characterized as a universal cold-formed C-shaped steel section. By entering nominal geometric parameters, the cross-section shape of cold-formed C-shaped steel can be located from the ten dots, and the coordinates of each position can be found through geometric relations to build a perfect cold-formed C-shaped steel component. Then use the following method to find the center of mass coordinates of the measured cross-section data and the perfect cross-section data, and overlap the center of mass of the two sections to provide reference for extracting global imperfection.

$$x_c = \sum_{i=1}^{n} x_i^{flanges} + \sum_{i=1}^{n} x_i^{web} + \sum_{i=1}^{n} x_i^{lip} \tag{1}$$

$$y_c = \sum_{i=1}^{n} y_i^{flanges} + \sum_{i=1}^{n} y_i^{web} + \sum_{i=1}^{n} y_i^{lip} \tag{2}$$

The three global imperfections of G1, G2 and G3 are all rigid body motion of the cross-section. For G1 and G2, the center of the two sections at the top and bottom of the member are selected as a straight line, and the center position of the perfect member aligned with it is expressed by coordinates. Then the size of G1 and G2 can be characterized as the maximum difference between the straight line upside down the length of the member and the center of the perfect member. It can be expressed in the following form. G3 selects the web as the reference plane and defines the imperfection size of the web along the rotation angle of the perfect member.

$$G_1(z) = x_c - x_{perf} \tag{3}$$

$$G_2(z) = y_c - y_{perf} \tag{4}$$

3. Case Study

The research mainly focuses on the extraction of geometric imperfections of cold-formed steel components, from high-precision obtained disordered point cloud data to point cloud processing and feature recognition, and finally extracting the initial geometric imperfections as reference parameters for experiments and finite element analysis. Next, a 450mm-long test component is selected as a case to show the extraction process and application analysis of imperfections.

First of all, according to the disordered point cloud, the algorithm is used to sort and cross-section the point cloud. The figure shows the sorted component point cloud, and the components are divided into 354 sections at an equal distance along the length direction(Figure 7). After storing it as Alldata, it is characterized according to the cross-section. Based on the robust feature recognition algorithm optimized above, feature recognition effectively and automatically processes the sorted point cloud model to help locate the geometric boundaries of the angular area and plane area in the cross-section. As shown in Figure8, the geometric characteristics of random cross-sections identified by optimization algorithms are stored separately between their curves and linear segments.

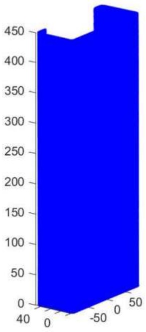


Figure 7：Generated measurement point cloud model

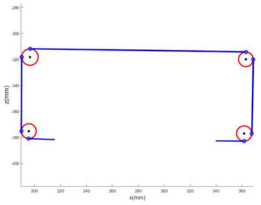


Figure8：Identification of geometric features

The three global imperfection G1, G2, and G3 are extracted. Using the method of calculating the center of mass of the actual measured section and the perfect section separately, so that they can be used as the co-location point, the co-location effect between the two is shown in the figure9. Then the center of mass of the perfect section is coincident with the coordinate origin, the change curve of the actual measured section with the center of mass of the length of the member can be obtained as shown in Fig10. Characterizing the global imperfections is most often considered by considering the maximum imperfection amplitude [1] , so the size of G1 and G2 is calculated according to the above equation(3、4). G3 is calculated by calculating the web offset angle to indicate the size of the torsional imperfection.

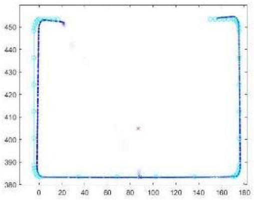
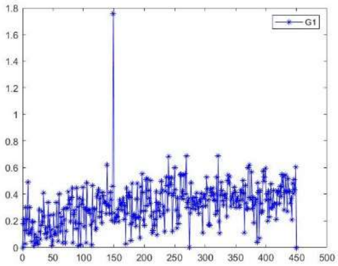
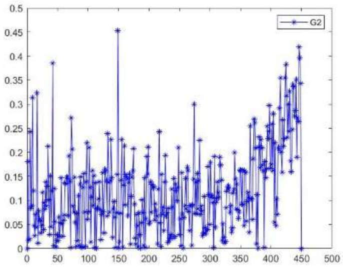


Figure 9：Comparison of actual measurements and perfect models





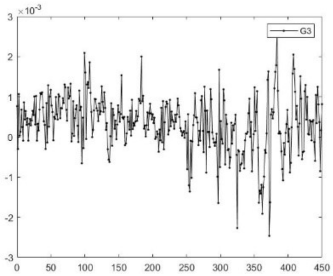


Figure 10：Typical G1, G2, G3 imperfections along the length

Based on the measured geometric point cloud data to obtain an accurate representation of the imperfection size, normal distribution fitting was performed to obtain the expected values and variances of G1, G2, and G3, respectively. The normal probability density curve (G2) was obtained by data fitting as shown in the figure11. Random imperfection data near the expected value are selected as input parameters to establish a finite element model based on the real measured member geometry and analyze the nonlinear analysis results of the member load capacity under a single variable of the initial imperfection.

The simulation analysis results in ABAQUS were extracted to obtain the deformation maps and stress clouds of the random imperfection data with G1, G2 and G3 applied respectively, and the load displacement curves of G1, G2 and G3 were selected and shown in Fig.12、13 for analysis.

	G_1	G_2	G_3（rad）
EV	0.316mm	0.119mm	0.000805
δ^2	0.164mm	0.088mm	0.000683

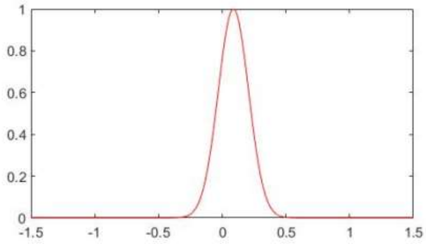


Figure 11：Normal density distribution graph

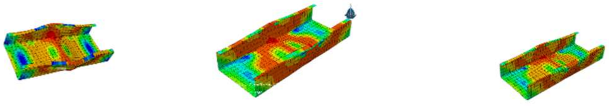


Figure 12：Stress-deformation cloud diagram of three imperfections

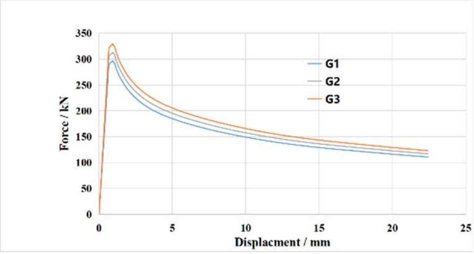


Figure 13: Load displacement curve under three kinds of defects

From the above, it can be seen that the bearing capacity of the rod tends to decrease with the increase of initial defects, so controlling the initial imperfection of the member has an important role in improving the bearing capacity of the rod. Secondly, the verification results can be seen that the G1 defect has a greater impact on the member among the three overall defects, which is in line with the theory.

4. Conclusions

High-fidelity geometric point cloud data of cold-formed steel members obtained by high-precision laser scanning technology and post-processed by the written algorithm can achieve a high-precision characterization of real-world members. The feature recognition algorithm can automatically identify the corner and plane areas of the cross-section, and the accurate representation of this boundary feature points is of great importance when extracting imperfections. Finally the imperfection size extracted by the method of this paper can be established as a nonlinear finite element model and verified with the deformation pattern of cold-formed C-section steel under axial compression test. This will establish reliable data support for the simulation of random imperfections in the next step.

5. Acknowledgments

This work was financially supported by Quota Project for Promoting the Connotation Development of Colleges and Universities - Young Scholars of Beijing Talent Project (02082721010), Basic Research Funds for Municipal Universities (X21062). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author (s) and do not necessarily reflect the views of the sponsors or other participants.

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