Automatic Approach for Measuring Deformations in Complex Structures Using Photogrammetry Technique

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Abstract:

This work presents an automatic approach for measuring deformations in complex structures and transferring that information directly to a finite element model for further structural analysis. Photogrammetry is used as a three-dimensional measurement technique to identify the displacement field from sets of digital images.

Three-dimensional deformation models of box girders are analyzed before and after a buckling collapse test. A comparison between the mechanically identified and based on the photogrammetry approach displacements has been performed. It is demonstrated that the output of the photogrammetry analysis can be used as a direct input to analyze imperfect structure based on finite element method. The procedure is validated against direct measurements.

Keywords: Photogrammetry; 3-D deformation measurement; FEM

1. Introduction

The current trend for ship structural design is to minimize the plate thickness of the ship's structure, in order to minimize the ship's weight and, therefore, maximize the ship's payload, in which accurate and reliable three-dimensional (3D) measurements are required. It is essential to have the ability to have a reliable and effective method of obtaining three-dimensional structural models, and to accurately measure the size and shape of structural deformations.

To model and measure the deformation of structures, image-based modeling techniques (mainly photogrammetry and computer vision) have received a great attention, from both experts and non-experts. The techniques are generally preferred for 3D documentation and modeling applications due to low budgets and adequate precision. Currently digital cameras equipped with 10-12 mega pixel sensors are very cheap comparing to range sensors, and furthermore they can be used for data acquisition in image-based modeling techniques, to photograph objects of any size and at various distances, using various focal lengths.

The photogrammetry technique, which employs a three-dimensional measurement technique and central projection imaging as a fundamental mathematical model, has been shown to be an effective method for collecting data about complex shapes, providing repeatable measurements over the past few decades. It is the first remote sensing technology ever developed in which geometric properties about objects are determined from photographic images. Automation of the image processing greatly speeds up the process of recognition. Close range photogrammetry is relatively easy to use and provides a high degree of accuracy sufficient for ship structures which allows detailed view of the distortions introduced during the production process or later on during the service life. A benefit of photogrammetry is that a photo record is kept of all the samples that are measured, which allow the measurements to be checked in the future.

It was shown that the accuracy attainable with CCTV (closed-circuit television) and CCD (Charge Coupled Device) cameras is sufficient for many industrial and other applications. The limited “resolution” of the cameras required relatively large targets, but many more images can be acquired and processed, thus improving the reliability. Precise target location methods and positioning algorithms with suitable calibration techniques were a prerequisite for meeting the accuracy requirements (Beyer, 1995).

Fraser (1997) reviewed the application of analytical self-calibration to digital cameras. Computer vision perspectives were touched upon, the quality of self-calibration was discussed, and an overview was given of each of the four main sources of departures from collinearity in CCD cameras.

Mugnier (1997) demonstrated that existing topographic mapping software with GDOP (Geometric Dilution of Precision) error propagation analysis could be used with high-resolution CCD cameras for shipbuilding and industrial 3D “as-built” applications.

Photogrammetry has found many diverse applications in the fields of industry, biomechanics, chemistry, biology, archaeology, architecture, automotive, and aerospace, as well as accident reconstruction. Although photogrammetry has not been as popular in shipbuilding engineering as in other fields, the investigations that have been conducted demonstrate the potential of this technique.

Goldan and Kroon (2003) presented the results of a multiyear project, which focused on improving lead time and economic efficiency in ship and offshore platform repair and conversion. Existing and newly developed photogrammetric measuring techniques were used to generate as-built models of double curved three-dimensional surfaces of ships and platforms. It was demonstrated that the digital photogrammetry has matured as a useful technology for automatic generation of as-built models of ship hull parts. It had also clearly demonstrated that lead time for damage survey and using the developed method can reduce measuring time significantly.

Cheng et al. (2005) introduced the digital photogrammetry method of solid modeling based on remote sensing an image pair. They have proved that the method of modeling had the characteristics of high precision and speed, and realized great balance between demand of speed and fidelity.

Lightfoot et al. (2007) used the photogrammetry method to measure the welding distortion in shipbuilding. It was intended that once the shipbuilders knew where the location and amount of distortion was occurring they could then alter production parameters or consider a different technique so as to try and reduce the distortion and minimize the cost of correction at later stages. It also concluded that photogrammetry is an inexpensive and straightforward manner to record surface deformation.

Jiang et al. (2008) presented a review of state of art on the basic development of close-range photogrammetry and briefly described previous work related to bridge deformation and geometry measurement and structural test monitoring.

Richardson and Richardson (2008) showed how a photo model of a structure can be used to create a finite element model (FEM) from which the nodes deflections of the structure can be calculated. The FEM may generate the shapes obtained from the photogrammetry models and then compared with the experimentally derived shapes of each structure to demonstrate the validity of this approach to FEA modeling.

Remondino and Menna (2008) presented new developments in terrestrial 3D surface reconstruction and object modeling using digital images, reporting some tests conducted using low cost digital cameras and commercial or in-house software and concluded that a successful image matcher and surface measurement approach should (1) use accurately calibrated cameras and images with strong geometric configuration, (2) use local and global image information, to extract all the possible matching candidates and get global consistency among the matching candidates, (3) use constraints to restrict the search space, (4) consider an estimated shape of the object as a priori information and (5) employ strategies to monitor the matching results.

The results of a digital photogrammetric survey, performed on the 81-foot Italian Navy motor yacht “Argo”, were presented by Menna et al. (2009). 540 circular coded targets were uniformly positioned on the hull surface, and approximately 75 circular code targets were also positioned on both the screw propellers. A 12 Mega pixels DSLR camera was used for the image acquisition. About 400 pictures of the boat surface and 60 images per screw propeller were taken with both parallel and convergent camera axes.

A photogrammetric approach for measuring weld-induced initial distortions in plated structures was presented by Chen et al. (2011). Compared with initial imperfection classifications, a new equation to predict the initial imperfections of very-thin-walled structures has been developed.

This work here presents an automatic approach for measuring deformations in complex structures and transferring that information directly to a finite element model for further structural analysis. It is demonstrated that the output of the photogrammetry analysis can be used as a direct input to analyze imperfect structure based on finite element method.

2. Data Acquisition and Calibration

Photogrammetry is a three-dimensional measurement technique which uses central projection imaging as its fundamental mathematical model often associated to a simple device called the “pinhole camera”. Three elements are sufficient to fully describe the perspective of a pinhole camera: the focal distance and the two coordinates of the point where the optical axis intersects the image plane (Interior Orientation), referring to a specific frame on the image plane. The camera calibration procedure retrieves perspective elements, known as Interior Orientation (IO) parameters, together with the radial and decentring lens distortion parameters, known as Additional Parameters (AP). Photogrammetry is able to get three-dimensional (3D) data of an object from images in a way that is very similar to theodolite survey techniques, since it is based on the intersection between two or more optical rays (redundancy) called collinearity straight lines in photogrammetric terminology. Within the perspective model, the object point, perspective centre and image point lie on the same collinearity straight line. The image acquisition stage consists in taking photographs of the object from different view positions, ensuring good intersection between collinearity straight lines. The photogrammetric process is strictly linked to marking some homologous object points on the images to determine both camera positions and orientations, called Exterior Orientation (EO), as well as 3D point coordinates. The recognition of the same object point on two or more images (image correspondences) requires the object surface to have enough texture information (such as natural points and/or edges, etc.). If no features are visible on the images, then artificial targets must be positioned and/or synthetic patterns must be projected or painted on the surface object. For some applications, i.e. for high automation and accuracy purposes, circular coded targets should be positioned on the object to automatically recognize image correspondences.

While IO establishes the geometric characteristics of a bundle of rays, the EO establishes its position and orientation with respect to the object space coordinate system. Each bundle requires six independent parameters: three for position and three for orientation. These parameters can be calculated either through the knowledge of at least three object points coordinates (single image orienting or resection method) or by marking the same object points (at least five) on two or more images (image pairs orienting or relative orientation method). Once the approximate values for exterior orientation parameters have been computed or estimated, a least square evaluation by means of a bundle adjustment process (multi image orienting) is performed in order to improve accuracy.

Once the exterior orientation parameters have been computed, different kinds of 3D measurements are possible (points, segments and/or straight lines, planar geometric shapes, solids, etc.). Generally, a rough approximation of accuracy achievable with photogrammetric measurements can be derived directly from uncertainty in marking the imaged geometric primitives.

Figure 1 illustrates the model presented by Gomercic and Jecic (2000), for reconstruction of a light rays uses two sets of coordinates, where (x, y) represents the position of an observed point projection in a photograph.

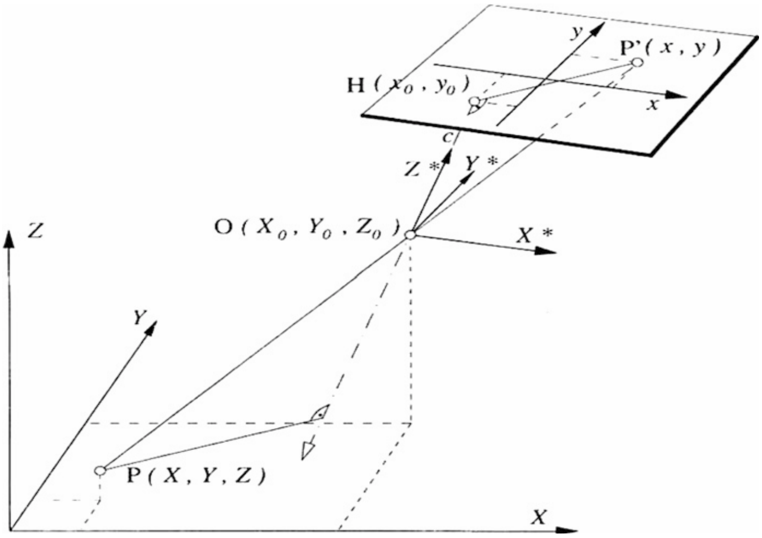

Figure 1: Relation between object and photograph point

Reconstruction of an optical straight-line consists in establishing a functional relation between the object and image coordinates. This model is sufficient for considering a measurement in the plane with two unknown values of the object coordinates X and Y, ($Z = 0$), and they can be calculated using two equations of image coordinates (x, y).

A 3D measurement includes three unknown values of object coordinates X, Y, Z. Two equations of image coordinates are not enough for calculation of three coordinates. Additional equations of image coordinates are necessary to solve the problem. The object point has to be recorded from another position, which gives two additional equations. The system of the equations is predefined. The optical measurement techniques for calculation of a point position in space are based on stereoscopic effect. A 3D position of a point is determined by triangulation, as shown in Figure 2.

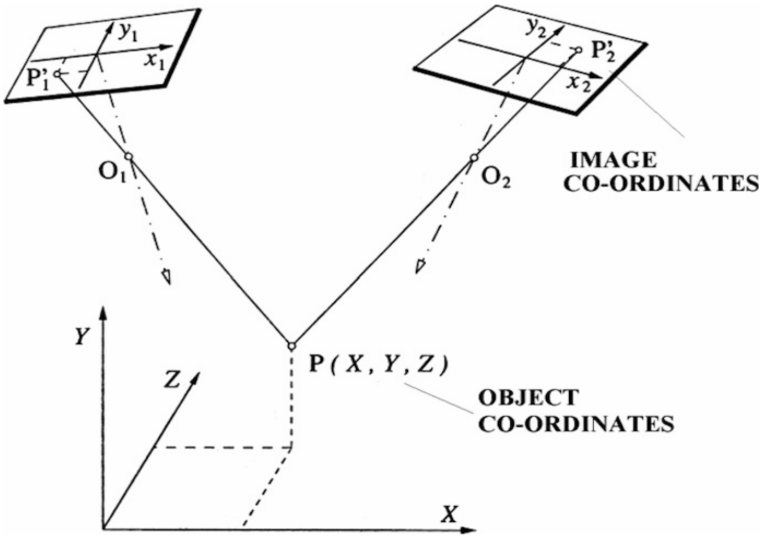

Figure 2: Triangulation principle

The position of a point is determined from an intersection of straight lines. The lines are defined by a point P and its projections points P_1' and P_2' on photographs. It is necessary to set up additional equations in order to record the point from another camera position and make a redefinition of the system, i.e. a larger number of equations than unknowns possible. The system of nonlinear equations redefined in this way is solved iteratively by an error minimization method, and the outputs of this analysis are 3D coordinates of measuring points and other parameters of the mathematical model.

3. Measurement Process

Along the ship service life, the ship's hull is exposed to many types of loads and subjected to different damage scenarios; one of these scenarios is corrosion deterioration that reduces the expected ship hull strength in intact condition. In the past decade, there has been a major worldwide concern about the continuous loss of some large tankers. A major contributing factor to the cause of these losses is considered to be catastrophic structural failure. The hull girder ultimate capacity is an explicit control of the most critical failure mode for large double hull tankers. In order to gain safe and economic design of ship structures, it is necessary to accurately evaluate the ultimate strength of deteriorated hull girders.

Figure 3: First box girder, before and after the tests

Figure 4: Second box girder, before and after the tests

Saad-Eldeen et al. (2011) carried out a series of experimental buckling collapse tests on box girders which are of 1400×800×600 mm^3 dimensions and divided into 3 bays by the web frames (see Figure 3 to 5). In these tests, the three box girders which represented the sections amidships are subjected to different levels of corrosion.

Figure 5: Third box girder, before and after the tests

A professional software for 3D modeling and measurement, (PhotoModeler®, 2009), was used to collect the image data from the test specimens.

Before the image acquisition, 12 photographs of the calibration grid which provided by the software supposed to be taken from twelve different positions and angles, and then be imported to the software to finish the calibration process.

A normal 12 mega pixels Digital Camera (DC) was used in this application for the image acquisition. The DC has a 12-megapixel sensor, a 5x zoom lens equivalent to 28-140mm with optical image stabilization, a three inch wide-view LCD monitor with 230k dot resolution. When processing the photographs, some selected points need to be marked and then be cross-reference in photographs taken from various angles. Compared to the conventional photogrammetric procedures, PhotoModeler® allows even greater reduction of time and costs for the production of models, since it does not require positioning and measuring of targets and stereoscopy to produce suitable photographic documents.

It has been shown that the method of measuring facades with the PhotoModeler software is efficient when having common points easily identifiable at least on 3 or 4 photographs, and this was sometimes impossible depending of the kind of object being measured and the characteristics of its surface and materials. The present experience has shown that the use of clearly identified and well-distributed high-resolution targets over the facades was recommended.

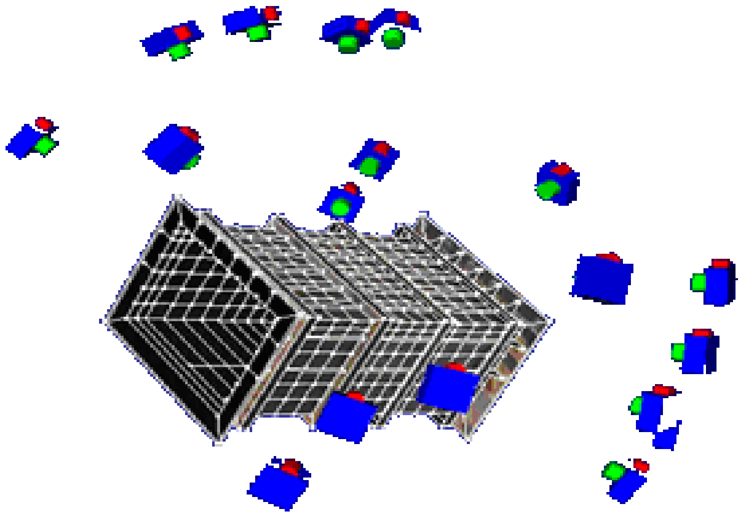

Figure 6: Box girder model and camera stations in PhotoModeler

Therefore, when for taking photographs after the calibration process, each selected point must be visible at least in two photographs that have been taken at an angle larger than 45 degrees to the object (see Figure 6). And it is well acknowledged that more photographs with the same points make more accurate results. Ideal lighting conditions had been arranged for a uniformly light scene during the image acquisition process, thus for not producing hard shadows which make points difficult to mark and reference.

Figure 7: Coded targets attached to the box girder

The automation of 3D point extraction and/or the project setup (initial marking, referencing and orientation of photos) can be performed by using the coded target. A coded target is a high contrast dot with a pattern around it that is placed in the scene before photography (see Figure 7). Since each coded target has a unique pattern, all the targets can be identified automatically by the program from the images.

All photographs were well focused. Once a good number of points have been marked, they need to be cross-referenced. The points in the proposed order are supposed to be selected in the second photograph, following the prompts in the first photograph. After the referencing of all points needed, the model can be processed into a 3D model, where the surfaces can be added between points or lines. When the surfaces exist in the model, the textures could be mapped onto the surfaces to make the model looks exactly the same as the reality.

4. Experimental and Photogrammetric Deformation Measurements

In the ultimate strength test, the deck of the box girder had been subjected to a compressive load that leads to a buckling failure mode. Due to this reason the deck was marked by 198 points on each specimen and matched in more than 20 photographs of the box girders both before and after the test. In the working coordinates system, the x+ direction is from right to left, and the y+ direction is from downward to upward. The photogrammetric initial 3D imperfection of the deck is shown in Figure 8.

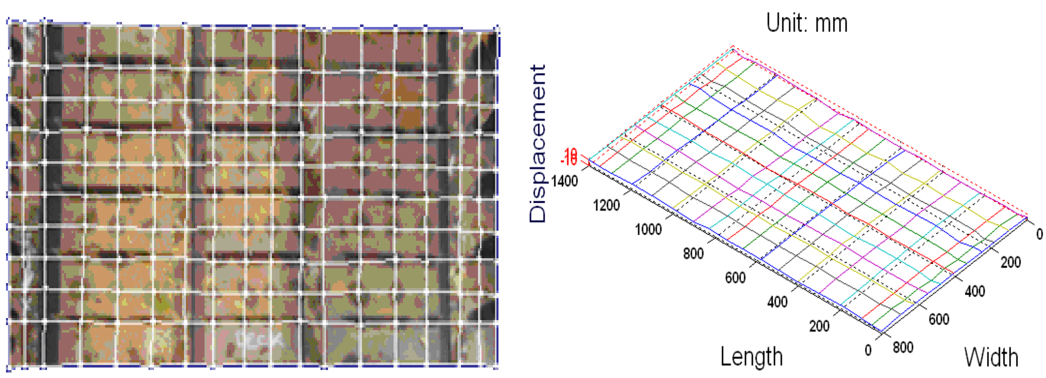

Figure 8: Deck surface before testing, first specimen

Initial imperfections on each deck of the box-girder had been analyzed. Fitting Log-normal probability density function and their statistical descriptors, the mean value of all the deformations downwards is equal to -4.157 mm, while the standard deviation is 3.425 mm. The mean value and standard deviation for the deformations upwards are 3.54 mm and 2.327 mm respectively.

After importing all photographs, the detailed location of each point and distances between points are also available when the modeling process has been done, which can make it possible to obtain the information such as the values and the shape of distortion in specific plate fields. Having the coordinates of each selected point, the surface plot can be easily accomplished. The 3D surfaces of the decks of the 3 different box girders are displayed in the following figures. For the first specimen, the biggest deformation occurred in location (1100, 625) in the third bay of the structure (see Figure 9). Validating the results of the first box girder for instance, the worst Precision Vector Length (PVL) is 0.7885 and the average PVL value is equal to 0.5931, which proved the acceptable precision of the methodology.

Figure 9: Experimental and photogrammetric decks surfaces after test, first specimen

Figure 10 shows the photogrammetric deck displacements after the test. In the case of the second specimen, it can be observed that the global post-buckling deformation achieved after the collapse test was more symmetrical. The lateral buckling displacement achieved in the second bay was upwards while the ones in the first and third bay were downwards. It has been noticed that the biggest deformation of the bay No.2 occurred in location x=732, which meant that centre of the buckling wave amplitude in the bay no.2 was shifted a little towards the bay no.3. While for the third specimen, the severe deformation happened in the bay No.3, which is the same as the first specimen. However, the deformation in this case became upwards, which is total opposite of the first case.

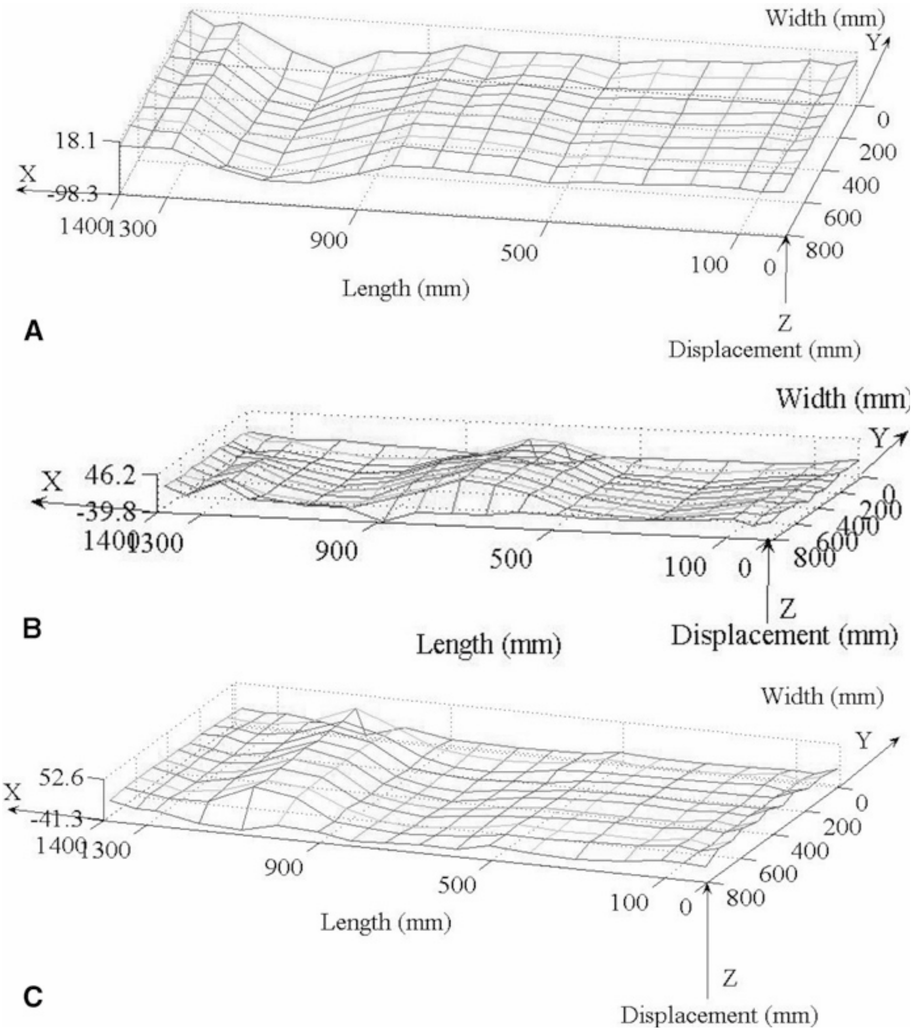

Figure 10: Photogrammetric deck displacements after test, A-first, B-second and C-third specimen

To investigate the deck deflections, the initial and post-buckling surfaces deflections have been analyzed and regression equations have been proposed by Chen et al. (2010), and some statistical analyses have been performed as well.

The judgment of the adequacy of the photogrammetric measurements is performed by the coefficient of determination, R^2, which defines the proportion of variability in a data set that is accounted for by the model (Steel and Torrie, 1960). It provides a measure of how well outcomes are likely to be predicted by the model.

There is some variability of the mechanically measured and predicted by the photogrammetry displacement.

The R-square factors for the deformations before and after the tests are 0.6028 and 0.7813, respectively, which implies that the observed and predicted deformations are relatively in good agreement. For the comparison of the second and third specimens (see Figure 10 B and C), the R-square factors are 0.6753, 0.6145, 0.3947 and 0.5561 respectively. To sum up, all the six R-square factors, except 0.3947, are larger than 0.55, which indicated a relatively good matching.

5. Finite Element Analysis

The final photogrammetric model is able to be exported into many different formatted files and to be used in various engineering programs. For instance, it can be exported as a '.dxf' file which can be used in AutoCAD, or a '.igs' file which will be used in ANSYS (2009) (see Figure 11), in which the processing and post-processing would be performed. The imported model is equivalent to the model done by operations of generating the points, lines and areas in ANSYS. After attributing the geometrical properties, the post-processing analysis could be done as requested.

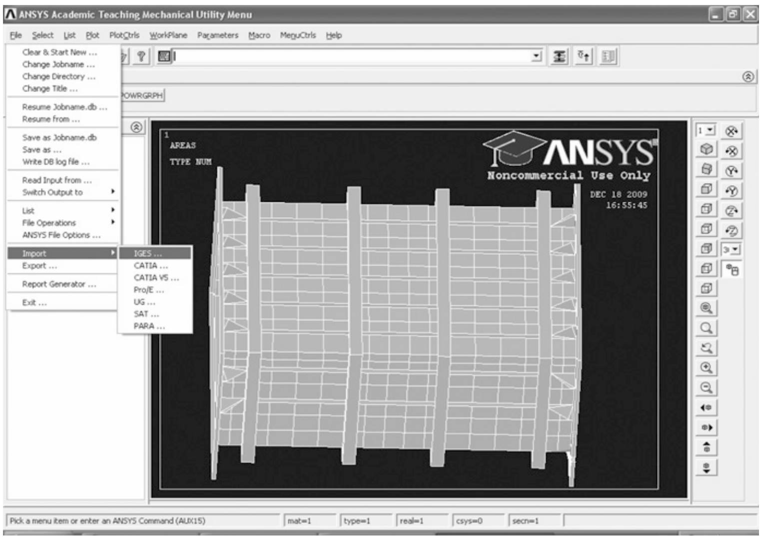

Figure 11: Importing model in Ansys

Constrained all nodes in one end section, and applied equivalent forces to a design vertical bending moment 377 kN·m on all nodes in the other end section (see Figure 12), a finite elements analysis based on the photogrammetric model of a box girder in ANSYS is presented.

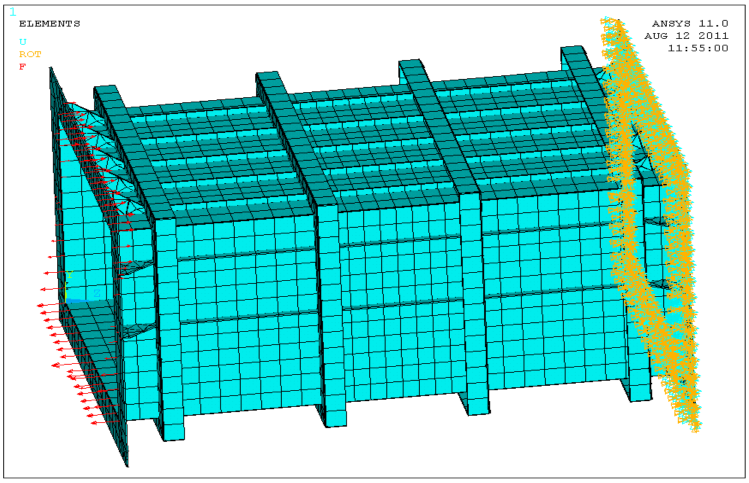

Figure 12: Boundary condition of FE model

The maximum Von Missed stress occurs in the intersectional place between the middle stiffener and the third web frame (see Figure 13). Three paths in deck, side and bottom at the middle of the second bay were created to extract the Von Misses stresses.

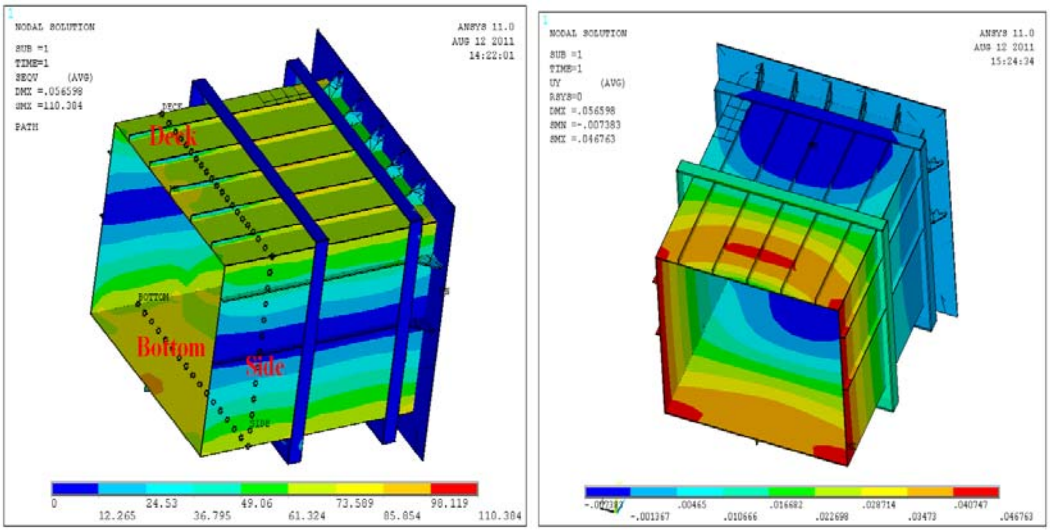

Figure 13: Von Missed stress and displacement distribution, first specimen

In the deck, the stiffeners are subjected to the biggest stresses, as shown in Figure 14 (absolute values). Especially in three of them in the middle, the stresses can reach more than 73 MPa. While the stresses in the deck plate gradually reduce from the middle to the edge of the plate width. Since the asymmetric locations of the stiffeners, the neutral axis of the section is locate in 39.1 mm above the middle of the height, which results in bigger stresses occurring in the bottom rather than deck. Maximum stress is observed in the only stiffener in the bottom plate, whose value is about 76 MPa. The minimum stress in the bottom is located at two edges of the plate, which is still no less than 72 MPa.

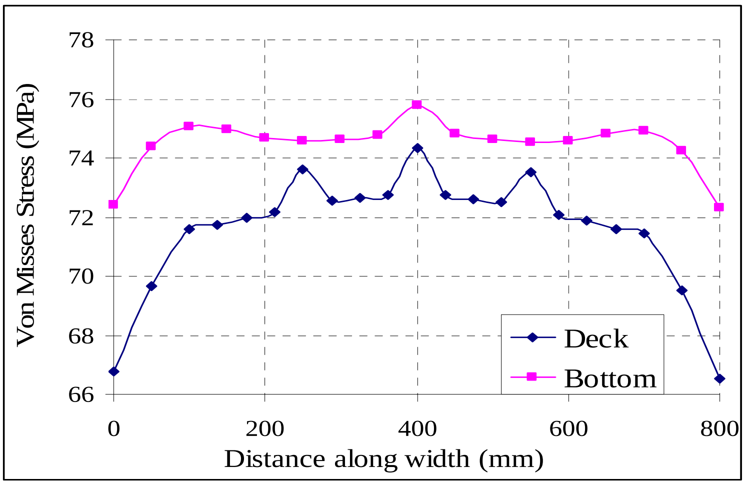

Figure 14: Von Missed stresses result on the second bay, first specimen

The distribution of Von Misses stresses is more uniformly linear in the side plate. The absolute value of the stresses in the left end in Figure 15 is correspondent to that in the edge of the deck, while the one in the right end is the same as that of the edge of the bottom. The minimum stress is close to zero. It locate near the middle of the side plate and a little toward the deck, which is identical to the position of the neutral axis.

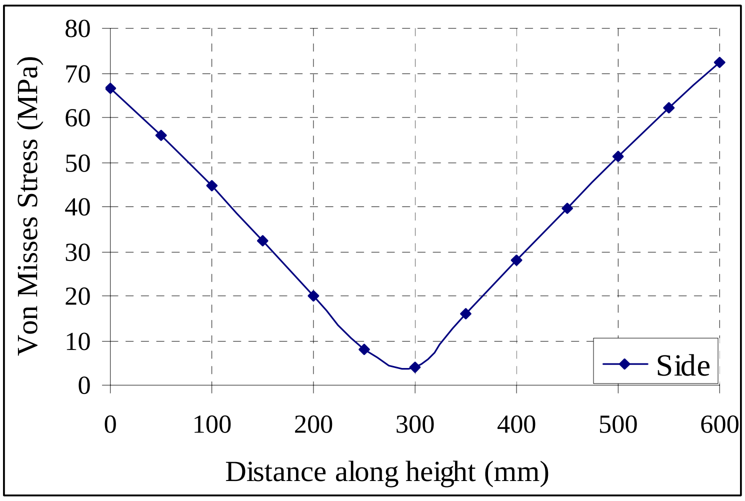

Figure 15: Von Missed stresses, second bay, first specimen

The lateral displacement achieved in deck of the second bay is upward while the one in the deck of third bay is downward (see Figure 13 right). The displacement distribution is to some extent uniformly linear in the second bay. A maximum deformation in second bay is located near the middle of the deck plate as well as the edge close to the web frame in side plate. While the shape of displacement contour in the third bay are similar to an ellipsoid, from one side closer to the end section to the other side.

6. Conclusions

An automatic approach for measuring deformations in complex structures and transferring that information directly to a finite element model for further structural analysis is presented in this work. Photogrammetry is used as a three-dimensional measurement technique to identify the displacement field from sets of digital images.

Three-dimensional deformation models of box girders are analyzed before and after a buckling collapse test. By means of the coefficient of determination of the photogrammetry errors, the results achieved are proved to be very successful and can be used as an input for finite element analysis.

This study has shown a good ability of the photogrammetric approach to provide high resolution 3D models of deformed surfaces and demonstrated its effectiveness. It is also demonstrated that the output of the photogrammetry analysis can be used as a direct input to analyze imperfect structure based on finite element method.

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