Load Testing Measurements for Structural Assessment Using Geodetic and Photogrammetric Techniques

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Key words: deflection modelling, load test, close range photogrammetry, photo-triangulation, finite elements

SUMMARY

The methodologies used for the design of large manmade structures are mainly based on information about the materials, which is obtained experimentally using small-scale specimens and simplifying assumptions with regard to the geometry and the behaviour of structural elements and structural components. Displacement measurements in structural elements, like beams, in laboratory-controlled conditions constitute a very useful tool for the validation of the theoretical design models and material behaviour. These measurements are usually taken at specific positions on the structural element.

In this paper the behaviour of a timber beam under five-point bending conditions is examined both theoretically and experimentally. The objective of this research is to use geodetic techniques, specifically conventional surveying and digital photogrammetry, to describe a beam undergoing controlled loading.

Whilst both the above geodetic techniques provide non-contact measurement systems, photogrammetry has the advantage of rapidly recording detailed and definitive three-dimensional information over the entire surface of the beam as opposed to traditional sparse point-wise structural displacement observation techniques (e.g. dial gauges, LVDTs). Measurements of displacements are taken for a number of load levels. The test results are compared with analytical results using the finite element method for orthotropic behaviour of the timber beam. occur

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1. INTRODUCTION

The design of large manmade structures is mainly based on information about the materials, which is usually obtained experimentally. Small-scale specimens are used and simplified assumptions are made with regard to the geometry and the behaviour of structural elements and structural components. Displacement measurements in structural elements, like beams, in laboratory-controlled conditions, constitute a very useful tool for the validation of the theoretical design models and material behaviour. Whilst load testing supplements numerical calculations by giving measurable responses, it is critical to provide such information from a large number of points distributed on the surface of the test component. The typical instrumentation used in load tests is only capable to measure effects on restricted number of points of the surface.

Methods that are capable of measuring in a non-contact way a large number of points and provide a complete and detailed description of the surface of the beam are available and can be implemented in this type of engineering application. Such methods yield high accuracy estimates of deflection in two or three dimensions and provided that suitable hardware and software is used, deflection values can be produced in real time. Specifically, these methods are:

- Geodetic techniques implementing theodolite intersection for the 3D coordinate determination of predetermined points on the surface of the beam by the acquisition of high precision angle measurements
- Photo-triangulation using bundle adjustment, a digital photogrammetric method that determines 3D coordinates of a large number of points in a single adjustment (e.g. Jauregui et al, 2003; Fraser et al, 2003)
- Videometry, a digital photogrammetric method using video images that provide 3D information in real time (e.g. Tournas, 2003)
- Terrestrial laser scanning with the ability to amass enormous and very dense 3D data sets makes a potential alternative method to traditional sensors for structural deformation monitoring (e.g. Gordon et al, 2003; Lichti et al, 2002).

This paper will concentrate on the implementation of two of the aforementioned methods, namely the photo-triangulation and standard surveying intersection for the measurement of deflections of a loaded wooden beam. Videometry is an attractive method for dynamic monitoring but requires the use of expensive cameras in order to achieve the desired accuracy. Laser scanning is a very promising technology but is largely untested in this area. The main objective of this paper is to examine the effectiveness of geodetic techniques to measure displacements at various points of the beam. Details using the two geodetic measuring techniques to rapidly acquire accurate and three-dimensional information during the load tests are first presented, followed by the analysis of the data. The experimental data, which were also supported by measurements from a dial gauge, were compared with theoretical results using the finite element method. Finally, a discussion on the advantages of geodetic methods in supporting load tests concludes this paper.

2. EXPERIMENT INVESTIGATION

The static load experiment involved the controlled loading of a timber beam made of white fir in order to determine its deflection response. The beam of dimensions 1.5m x 0.14m x 0.07m was placed on an indoor hydraulic jack system, as shown in Figure 1. Both faces of the beam were accessible for visual inspection and surface measurements.

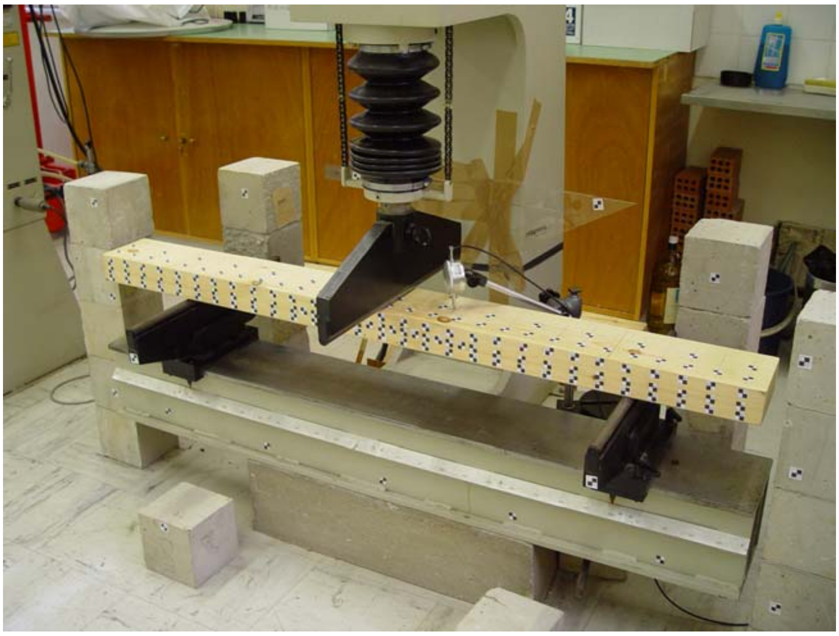


Figure 1: The timber beam positioned on a hydraulic jack system

The beam was vertically supported close to its two ends while the loading jack was located at the centre of the beam. Measurements with the dial gauge were taken at five load levels (8, 12, 17, 20.5 and 23 kN) whereas measurements with the geodetic techniques were taken at three load levels (8, 12 and 23 kN). At the beginning of the experiment, a zero-load case was captured to allow comparison with the subsequent loads.

A total number of 140 targets were fixed onto the beam as shown in Figure 1. These consisted of a 20mm x 20mm paper with chequered black and white prints. The targets were affixed on three rows on the face side of the beam and on two rows on the topside of the beam, at approximately 5cm from each other. A number of 17 targets, also affixed onto stable components of the test frame and concrete blocks around the beam, acted as stable reference points for datum definition and control points for the photo-triangulation.

2.1 Instrumentation

Three different types of measuring techniques were used: standard surveying, close-range photogrammetry and dial gauges. At each load increment and before the next load was initiated, data using all three techniques were acquired.

Standard surveying using two totals stations was employed to perform coordination of the array of targets to a common reference system. Two total stations, a Leica TC1600 (quoted accuracy of 5cc in angles and ±3mm ±2ppm in distance) and a Leica TC1800 (quoted accuracy of 3cc in angles and ±2mm ±2ppm in distance) were used. These were positioned at approximately 2m from the beam and were recording simultaneously measurements (horizontal and vertical angles) to the same target in order to compute its location by the method of intersection. In each load increment, measurements were also taken to all targets outside the beam comprising the datum definition in order to check stability. Due to time constraints, effort was placed in the measurement collection from targets located at mid-span of the beam. Exceptional care was exercised in the execution of the survey, however the method required much time and it was difficult to collect data from all targets without failing to maintain the load on the beam.

The second method involved the use of close range photogrammetry. A Sony DSC-F707 digital camera with a CCD array of 2560 x 1920 pixels was employed. A digital camera of medium resolution of 5 Mpixel was used instead of a calibrated metric film camera of large format, in order to investigate the possibilities of a modern amateur camera being employed in an application were high accuracy is needed. Furthermore, the small size of the object (length of beam 1.5m) makes convenient the use of such a camera. All photos were taken at a distance camera-object of 1.5m. For each load level (zero level, 8kN, 12kN and 23kN) 9 photos were taken: 7 vertical photos with 70% overlap and a stereo-base of 0.25m (with $\omega \approx 10^{o}$) and 2 oblique photos taken from the edges of the beam (with $\varphi \approx 30^{o}$). Prior and after the experiment photos were taken for use in the camera calibration process.

Further to the aforementioned non-contact methods, a dial gauge, positioned in the approximate centre of the beam, was used to measure the vertical deflection of the beam in each load increment. The resolution of the dial gauge is at the level of 0.01mm. This sensor was used to provide an independent measurement in a single dimension. The setup of the sensor in the specific experiment was in such a way to measure vertical displacements.

3. ANALYTICAL MODELLING

The loaded beam was modelled using the finite element method and the commercial code ANSYS (ANSYS, 2003). The mesh used is shown in Figure 2. It is consisted of 5180 3D 8-noded solid elements. The mesh was created in such a way that the position of the load application and the support of the beam coincides with nodes. The support was modelled by restricting the displacement in the vertical direction. At the position of the load application and at the centre of the beam the corresponding node was restricted from moving in the width and axial direction in order to avoid rigid body motion.

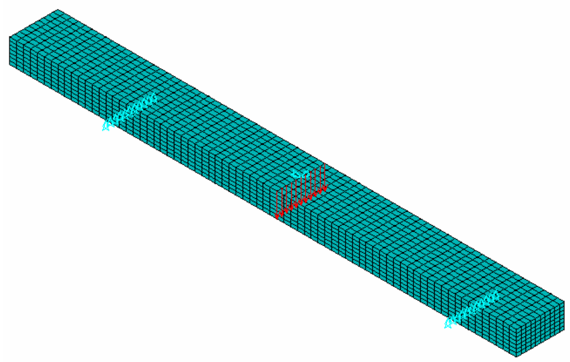


Figure 2: Finite element mesh of the timber beam

3.1 Orthotropic Nature of Wood

Wood may be described as an orthotropic material; that is, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial and tangential (Figure 3). The longitudinal axis L is parallel to the fiber (grain); the radial axis R is normal to the growth rings (perpendicular to the grain in the radial direction); and the tangential axis T is perpendicular to the grain but tangent to the growth rings.

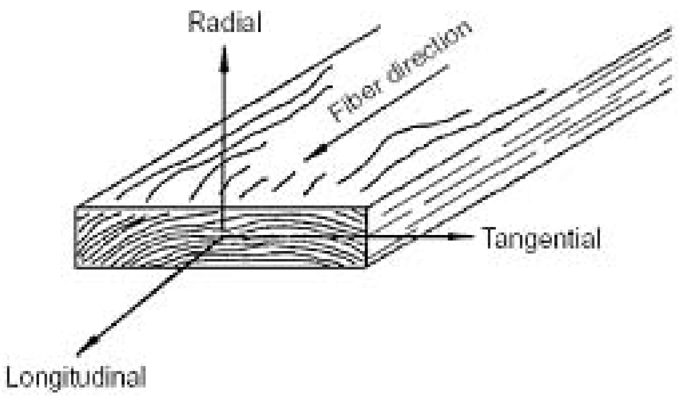


Figure 3: Three principal axes of wood (after Wood Handbook,2003)

To model this behaviour in the finite element analysis, the following nine independent constants were used: three moduli of elasticity (E_i), three moduli of rigidity (G_{ij}) and three Poisson's ratio (μ_{ij}), $i, j = L, R, T$. For the material of the beam (white fir) the following average values were taken from the Wood Handbook (2003):
$E_L = 9150$ MPa , $E_R = 933$ MPa , $E_T = 357$ MPa ,
$G_{LR} = 640$ MPa , $G_{LT} = 530$ MPa , $G_{RT} = 55$ MPa ,
$\mu_{LR} = 0.341$, $\mu_{LT} = 0.332$, $\mu_{RT} = 0.437$.
The average rupture strength of the white fir is 54.5 MPa.

3.2 Finite Element Results

Since the finite element analysis is elastic, the problem was solved only for one load case (8kN) and the results of the other load cases were taken as proportional to the applied load. Figure 4 shows the vertical displacement contour for an applied load of 8kN. The deformed shape is scaled by a factor of 10 for the displacement to be visible. The maximum vertical displacement is 5.1 mm.

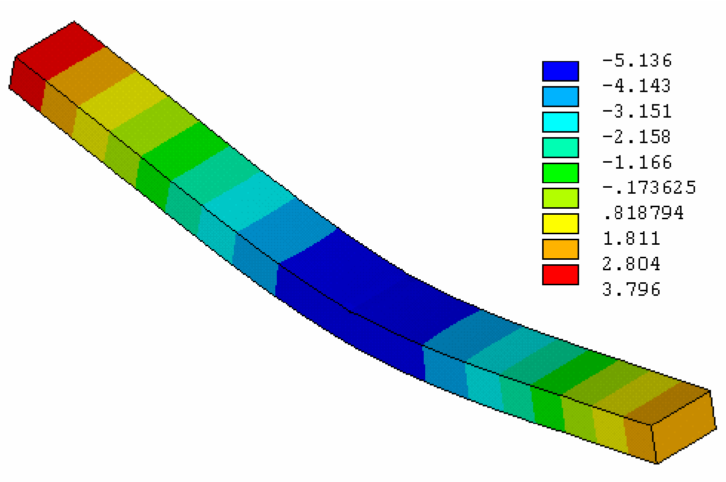


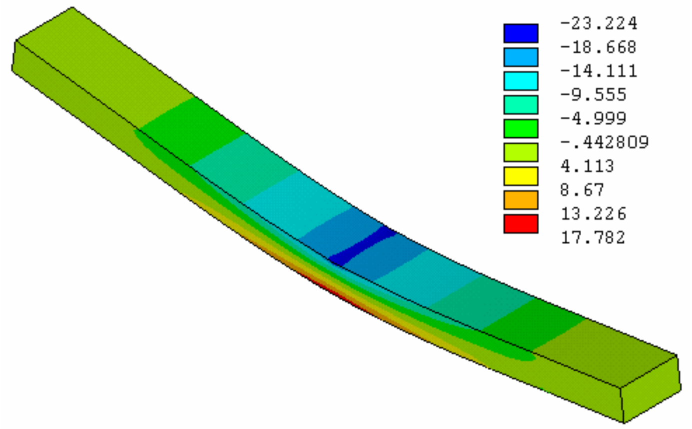
Figure 4: Distribution of vertical displacement for an applied load of 8kN

Figure 5 shows the distribution of the longitudinal stress for an applied load of 8kN. The maximum tensile stress is 17.8 MPa and the maximum compressive stress is 23.2 MPa. The difference is due to the sharp stress increase at the position of load application. Based on the maximum tensile stress of 17.8 MPa and the rupture strength of the beam of 54.5 MPa, it is estimated that the rupture load is 24.5 kN. This is very close to the experimentally obtained rupture load of 23 kN (Figure 6).

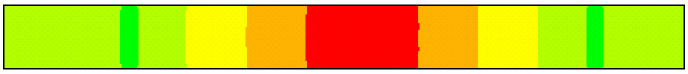
4. GEODETIC DATA PROCESSING

4.1 Geodetic measurements

Given the base distance between the two total stations, the coordinates of each target were computed using the observed angles via the intersection by the base solution. The estimated RMS coordinate standard deviations of the datum and non- datum points were σ_X = 1mm, σ_Y = 1mm, σ_Z= 2mm.



(a)



(b)

Figure 5: Distribution of longitudinal stress for an applied load of 8kN;
(a) general view, (b) bottom view

4.2 Photo-triangulation

The requirement of rapid data acquisition in each load increment during the experiment makes photogrammetry an attractive method for this type of application. However, the choice for the implementation of the most suitable photogrammetric procedure was defined by the

- required accuracy of the estimated coordinates being in the order of 1mm and
- relatively small number of the pre-marked control points onto the beam.

The use of photo-triangulation with bundle block adjustment covers more satisfactorily the above two requirements over the procedure of stereo-restitution of independent models and therefore it was the method that was finally implemented in this work. The processing of the data collected during the experiment was performed with the proprietary software BINGOv5. This software performs least squares adjustments of aerial- or close- range photogrammetric blocks with photogrammetric only data, or it uses combined adjustment with either known camera parameters or self-calibration and up to 30 additional parameters.

At this experiment, the digital camera that was employed was used with unknown calibration. The requirement of achieving high accuracy results necessitated the calibration of the camera. This calibration was performed using two independent procedures.

The first procedure involved the use of the reference targets that were affixed onto stable components of the test frame and around the beam. In-house software, written in Matlab, was employed that makes use of DLT (for the initial values) and collinearity equation (Samara, 2004). The procedure was applied twice, using one photograph taken prior and another taken after the experiment, with 17 reference targets as control points. The yielded results indicated stability of the camera characteristics in time.

Specifically, it was estimated that c = 2009.9 ± 3 pixel, x_o = -21.3± 3 pixel, y_o = 9.4± 3 pixel. Also, two radial distortion parameters (k_1, k_2), two tangential distortion parameters (p_1, p_2) and two additional affine parameters, describing verticality of the pixel axes and the ratio of the pixel dimensions, were estimated.

The second procedure involved the self-calibration procedure of the camera along with the least squares adjustment of all the unknowns of the photo-triangulation. Specifically, the unknowns of the adjustment using the data collected at the zero and at each of the subsequent loads, were the c, x_o, y_o parameters and two additional elements related to the radial distortion of the camera. The results in the four adjustments showed exceptional stability of the camera and the estimated values were: c = 2009.8 ÷ 2909.9 (± 0.5 ÷0.7) pixel,
x_o = -21.2 (± 0.5 ÷0.7) pixel, y_o = 9.4÷ 9.5 (± 0.5 ÷0.7) pixel ± 3 pixel.

Whilst the results from both calibration approaches are similar, the self-calibration process was finally chosen because both calibration and estimation calculations are performed in an integrated approach.

Figure 6: The timber beam under the last loading before the failure

4.3 Bundle Adjustment Results

The pixel coordinates of 92 premarked points (out of 157 points in total) were measured manually at the zero and at each of the subsequent loads. The premarked points included control and tie points; specifically, 65 were located on the front face of the beam, 15 on the top surface and 13 were control points.

A combined photo-triangulation and self-calibration processing of the data (§4.2) was performed separately for each one of the four data sets. Each least squares adjustment involved 822 observation equations and 421 unknowns (coordinates of points, elements of interior and exterior orientation). The RMS of the estimated coordinates was better than ±3mm and the aposreriori standard deviation (1σ) resulted in 1.7mm, 2.2mm, 2.0mm and 1.9mm for the adjustments at zero, 8kN, 12kN and 23kN loads respectively.

The 3D displacement at each point was calculated by simply subtracting loaded coordinates from non-loaded coordinates, given that all epochs of photogrammetric data have the same datum definition. The maximum deviations at the horizontal direction were 3mm, 4mm and 3mm for the three loads respectively. These deviations occurred at points located at the two sides of the beam but their magnitude is within the uncertainty level of the coordinate estimation. At the vertical direction, the maximum deviations occurred at mid-span directly below the point of the force load and deflection decreased near the ends where the beam was supported. The maximum deviation values were -6mm, -8mm and –17mm for increments of 8kN, 12kN and 23kN respectively. Figure 7 depicts the positions of the measured points, in XZ level, after each load increment. The vertical deflections are given at a scale of ten times larger than the scale of the beam for clarity.

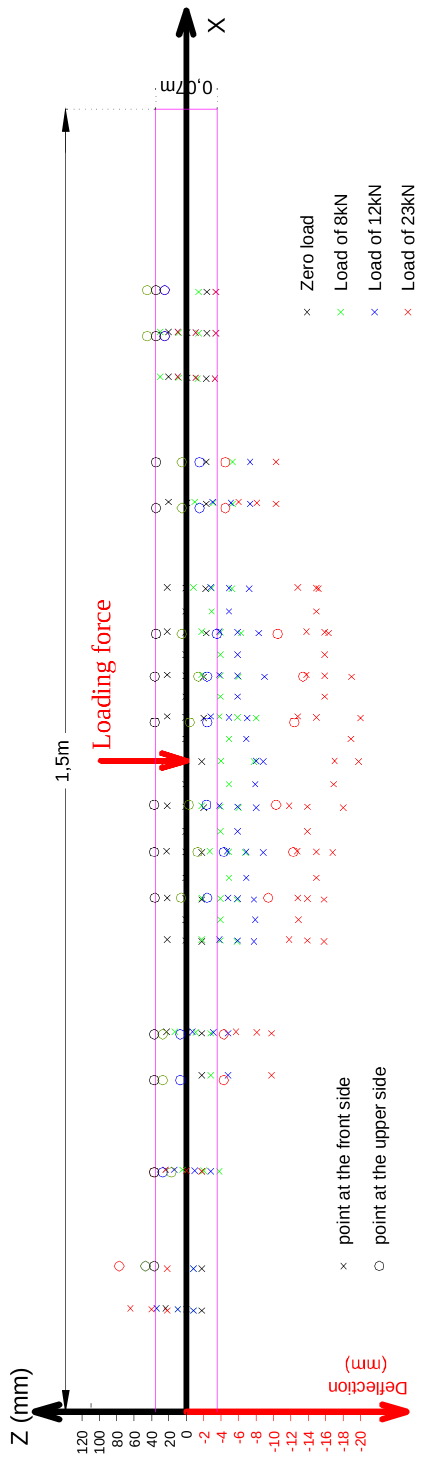


Figure 7: Photogrammetrically determined displacements

The zero load points are presented in black colour and the green, blue and red colours indicate the posistion of the same points for loads of 8kN, 12kN and 23kN respectively. The theodolite intersection method gave similar results for maximum deflection. The deflection differences between photogrammetric and theodolite measurements for the points located at the front face beam surface were in the order of ±2mm for the load of 12kN and ±1mm for the load of 23kN. These differences are statistically not significant at the 95% confidence interval. On the contrary, the result differences for points located at the top surface of the beam were varied. This can be attributed to the fact that there was restricted visibility to the targets affixed on the top surface of the beam from the two total stations.

5. COMPARISONS

Figure 8 shows the comparison between the vertical displacement measured with the dial gauge and the corresponding finite element results. The results are almost similar up to an applied load of 12 kN but deviate for larger loads. The reason for that is the non-linearity of the beam behaviour at larger loads due mainly to cracking.

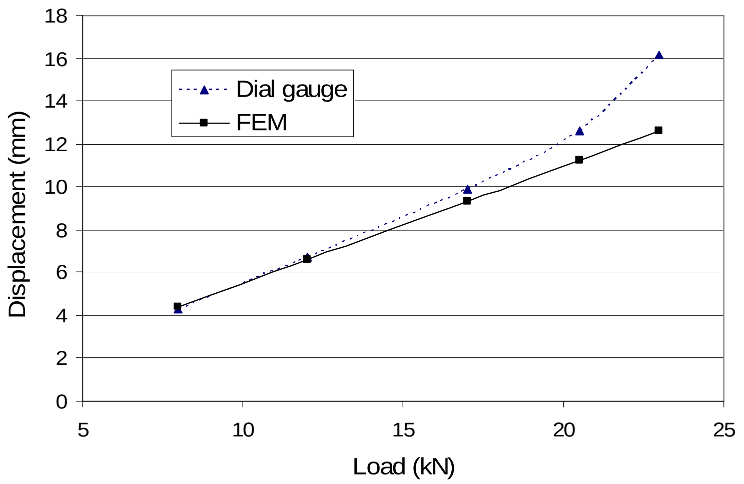


Figure 8: Comparison between dial gauge and finite element results

Figures 9 compare the measured vertical displacements using photogrammetry and the predicted displacements using the finite element analysis. The parabolic fitting of the results of the photogrammetric adjustment is also included in the figures. Figures 9 (a) and (b), for which the finite element analysis is valid, suggest that the average difference between the finite element analysis and the test data is in the order of 1 mm. This corroborates the accuracy of the photogrammetric data. Furthermore, the fitting curve of the test data describes very well the deflection of the beam. For a load of 23 kN, the linearity assumed by the finite element analysis is not valid, and the test data give bigger values for the displacement. This is in agreement with the measurements taken from the dial guage.

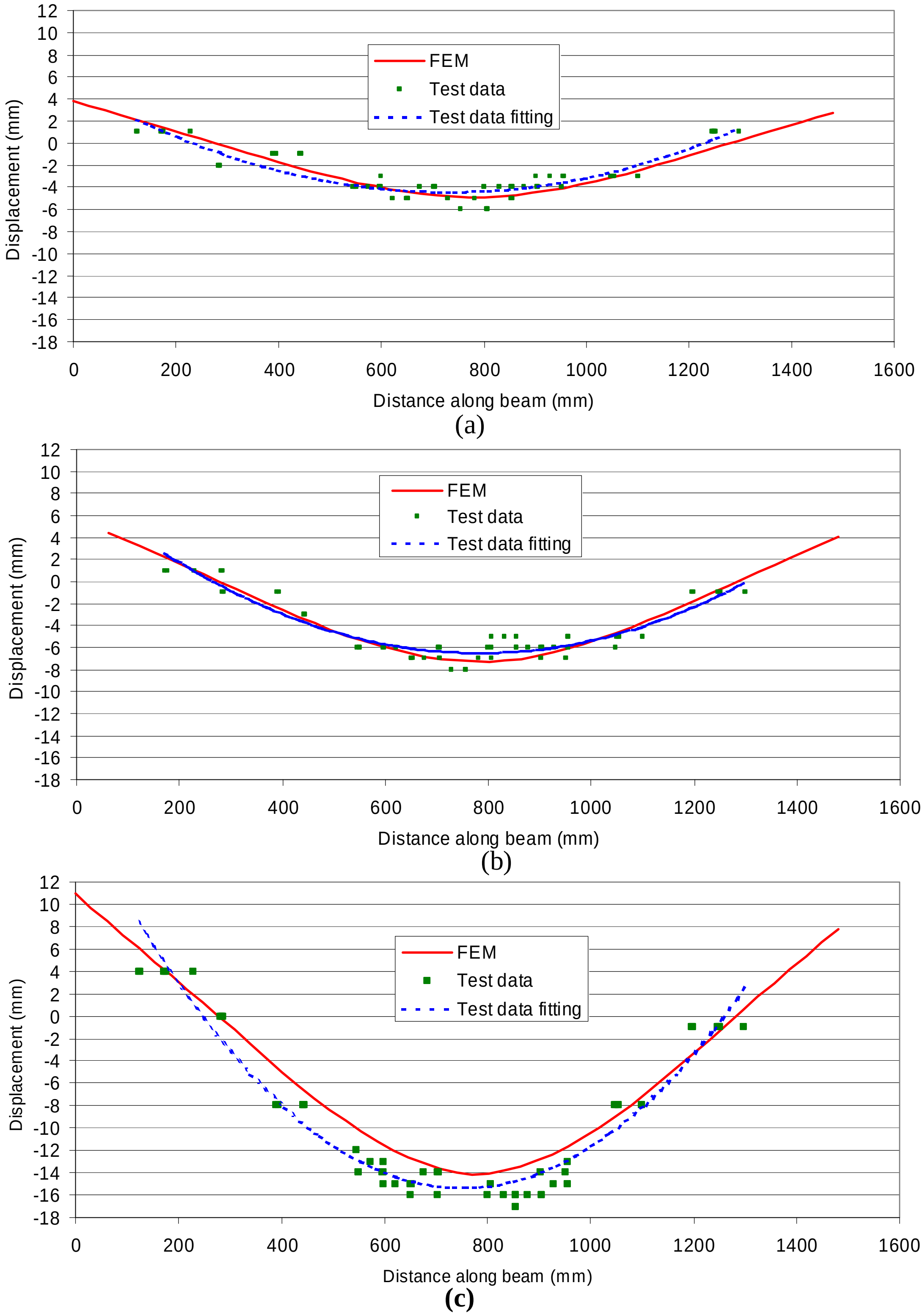


Figure 9: Comparison between photogrammetry and finite element results for an applied load of (a) 8kN, (b) 12kN, and (c) 23 kN

CONCLUSION

The implementation of geodetic methods, namely close-range photogrammetry and theodolite intersection, for the measurement of vertical deflections during the controlled loading of a timber beam has been presented. While both methods are of comparable accuracy, the acquisition of simultaneous measurements from two total stations is very slow and restricted number of points can only be measured. The photogrammetric results describe very well the deflection of the beam with an accuracy of approximately 1mm. Furthermore, the photogrammetrically derived deflections corroborate the dial guage measurements recorded during the load increments.

The analytical model representing the bending mechanisms of the beam was developed using finite element analysis. The estimated rupture load of the beam was 24.5 kN which is very close to the experimentally obtained rupture load of 23 kN.

Model-derived vertical deflections were compared with deflections derived from photo-triangulation adjustment. Results indicate that the average difference between the finite element analysis and the test data is in the order of 1mm which is in agreement with the accuracy of the photogrammetric measurements. Further research includes the combined use of photgrammetric and terrestrial laser scanner data for the complete 3D representation of the beam resulting also to the improvement of the analytical model.

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BIOGRAPHICAL NOTES

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