A Proposal of the Gage-Free Safety Assessment Technique for the Steel Beam Structure Under Uncertain Loads and Support Conditions Using Motion Capture System

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Abstract. Estimating the maximum stress through stress distribution of a structure is an important indicator for structural safety evaluation. Structural health monitoring can be used to do this with a variety of measuring equipment such as strain gage, LVDT, LDS. All the measuring equipment, however, has some weakness in the configuration of complex wire network and some inconvenience of replacing faulty sensors. Therefore, this paper suggests a technique that can estimate stress distribution of steel beam structure under uncertain load and support conditions by using motion capture system (MCS). MCS is a Vision-based Monitoring System, which measures 3D coordinates of multiple markers attached to the surface of steel beam without installing the complex wire network. In this study, the stress distribution is estimated from an analytic model by using displacement values measured by MCS. For the evaluation of the estimated stress distribution, comparing with the measured stress from ESG is performed.

Keywords: Structural health monitoring · Strain estimation · Structural safety · Steel beam · Maximum stress · Vision based monitoring · Motion capture

1 Introduction

In this study, a gage-free safety assessment technique for the steel beam structure is proposed. This proposed technique estimates stress distribution of the steel beam structure because the maximum stress is an important indicator for structural health monitoring. Stress distribution can be estimated from an analytic model using displacement values measured by motion capture system (MCS). MCS is a vision based monitoring system without complex wire network unlike conventional sensors such as strain gages, LVDTs, and laser displacement sensors (LDS).

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As shown in figure 1, there is no complex wire network between steel beam structure and MCS. Because MCS is a vision based monitoring system that can measure 3D coordinates of markers by using reflected light from each marker.

So, this system can measure 3D coordinates of markers under the gage-free condition. But, partially, MCS Camera, Server and computer is connected by wires. In this study, this issue is left for future research topic.

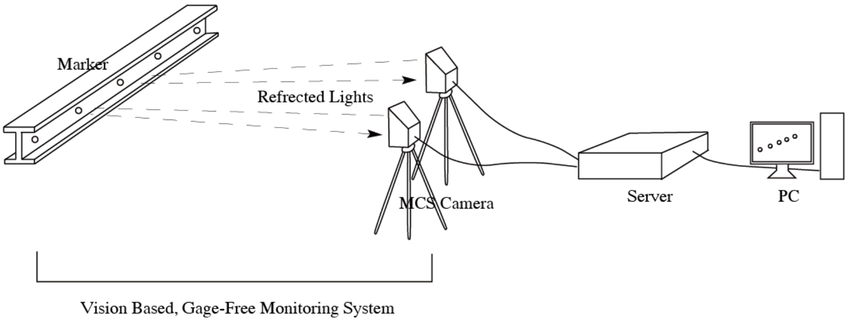

Fig. 1. Motion Capture System

From measured 3D coordinates measurement of each marker, stress distribution of the steel beam can be estimated by interpolation as well as deformed shape of the steel beam structure.

In order to estimate stress distribution, the radiuses of curvature of every point should be calculated first. In this study, a cubic smoothing spline is used for interpolating deformed shape of the steel beam structure, and numerical differentiation is used for calculating the radiuses of curvature at every point of the steel beam.

Consequently, only 3D coordinates measured by MCS are needed to estimate stress distribution, so this suggested technique in this paper is applicable to the steel beam under uncertain load and support conditions.

2 Proposed Stress Distribution Estimating Model Using MCS

2.1 Estimate Structural Deformed Shape Using MCS

With the use of MCS, a structural deformed shape can be estimated, when 3D coordinates of markers are measured which are attached to the surface of the steel beam structure. The markers should be attached to the measurement points on the steel beam structure, and more than two motion capture cameras should be installed in full view of the markers.

When the installation is complete, 3D coordinate system can be generated by wand calibration. Then, the installed cameras measure 3D absolute coordinates of the markers on the basis of generated 3D coordinate system. Once 3D coordinates of the markers are measured, a structural deformed shape can be estimated by finding the difference between 3D coordinates of initial state and deformed state, and by interpolating these data. In this research, cubic smoothing spline interpolation was used.

However, the generated 3D coordinate system through wand calibration may differ from the total coordinate system. Thus, it needs to be calibrated by coordinate transformation.

2.2 Estimate the Radius of Curvature from Structural Deformed Shape

When structural deformed shape is obtained, strain values at every point of structural deformed shape can be calculated from the radiuses of curvature at the same points. The relationship between strain and radius of curvature is as below.

$$\varepsilon(x) = -\frac{y}{\rho(x)} \tag{1}$$

Where y is the distance from the neutral axis and ρ is the radius of curvature.

Also, the radiuses of curvature at every point of structural deformed shape can be calculated by equation (**2**)

$$\rho(x) = \frac{(f'(x)^2 + 1)^{3/2}}{f''(x)} \tag{2}$$

In order to use the equation (**2**), it is necessary to calculate both the first derivatives and the second derivatives at every point of structural deformed shape.

For conducting numerical differentiation, structural deformed shape should be interpolated with very small intervals. In this research, cubic smoothing spline interpolation with 0.0001mm interval was used, and the first derivatives and the second derivatives at each point are calculated by numerical differentiation using Four-point central difference method (**3**) and Five point central difference method (4) respectively. These numerical method's equations are as below.

$$f'(x_i) = \frac{f(x_{i-2}) - 8f(x_{i-1}) + 8f(x_{i+1}) - f(x_{i+2})}{12h} \tag{3}$$

$$f''(x_i) = \frac{-f(x_{i-2}) + 16f(x_{i-1}) - 30f(x_i) + 16f(x_{i+1}) - f(x_{i+2})}{12h^2} \tag{4}$$

2.3 Estimate Strain and Stress from Radius of Curvature

Once the radiuses of curvature at each point are estimated, strain values at each point could be calculated by using equation (**2**).

And then, finally stress can be estimated by multiplying strain by elastic modulus. This relationship between strain and stress is as below.

$$\sigma(x) = E\varepsilon(x) = -E\frac{y}{\rho(x)} \tag{5}$$

3 Application to Stress Estimation Model of Steel Beam

3.1 Simply Supported Steel Beam Experiment

To evaluate this proposed technique of estimating stress distribution, simply supported steel beam experiment was conducted. In this experiment, H-shape Steel beam(100 x 100 x 6/8) was used and it was tested under two central concentrated load cases, one was 0.285tonf, and the other was 0.600tonf. Central concentrated load cases were generated by actuator.

4 motion capture cameras were installed to measure 3D coordinates at each measurement point of the steel beam and 17 motion capture markers (250mm space apart) were attached on the center of the web plate of the steel beam.

In order to verify applicability of estimated strain values, 14 strain gages were used as reference sensors. And these were attached on the top flange of the steel beam, 250mm space apart except for both ends and center of the steel beam.

Also, for verifying applicability of MCS as displacement measuring equipment, 5 Laser displacement sensors were used, at 500mm, 1250mm, 2000mm, 2750mm. 3500mm, respectively. The installation view of the steel beam experiment is shown below.

Fig. 2. The Installation View of The Steel Beam Experiment

3.2 The Results of Experiment

Although 17 motion capture markers (250mm space apart) were attached to the center of steel beam web plate, only 9 markers (500mm space apart) were used for analysis. It is because cubic smoothing spline interpolation with too large number of markers resulted in distortion of curvature.

So, in this research, the structural deformed shape of the steel beam under central concentrated load was interpolated from 9 markers' 3D coordinate data (500mm space apart) by using cubic smoothing spline interpolation. From this interpolated structural deformed shape, 17 displacement data (250mm space apart) was re-estimated.

Then, as mentioned earlier, radiuses of curvature and strain values at each point (250mm space apart) were estimated. Since stress at each point can be calculated by multiplying strain of elastic modulus, the evaluation of strain values was performed only. The results of this experiment are shown below.

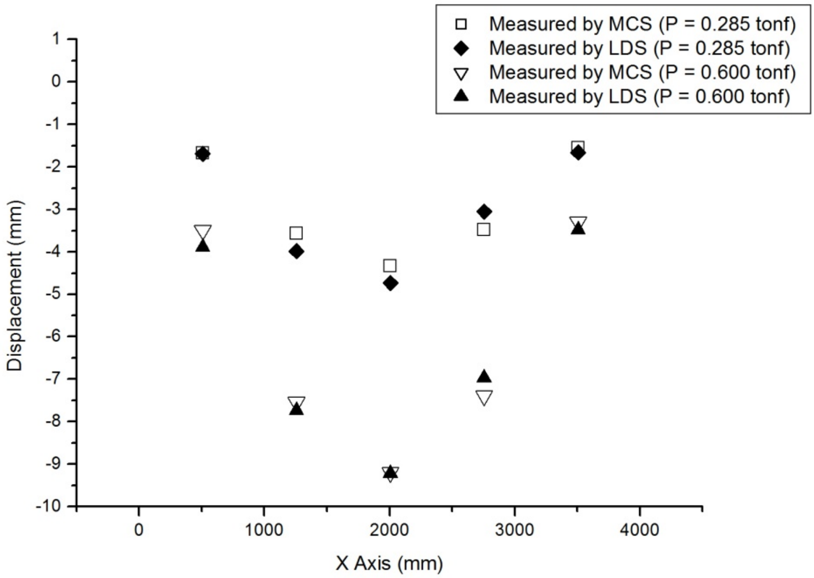

Fig. 3. Comparing with the Z-axis Displacements measured by MCS from measured by LDS

Table 1. The Error between Displacements measured by MCS from measured by LDS

X-axis (mm)	P = 0.285 tonf		P = 0.600 tonf	
	Absolute Error (mm)	Relative Error (%)	Absolute Error (mm)	Relative Error (%)
508.7	0.014	-0.839	0.397	-10.208
1256.0	0.418	-10.491	0.196	-2.533
2007.4	0.401	-8.472	0.025	-0.269
2756.5	-0.427	13.979	-0.422	6.046
3506.4	0.110	-6.603	0.191	-5.484
Average	0.274mm	8.077%	0.246mm	4.908%

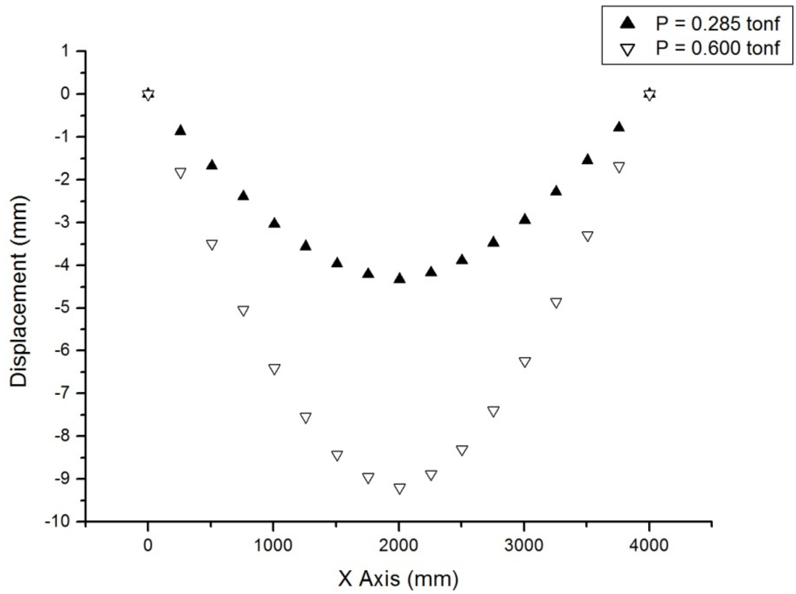

Fig. 4. Estimated Structural Deformed Shape for Each Load Case

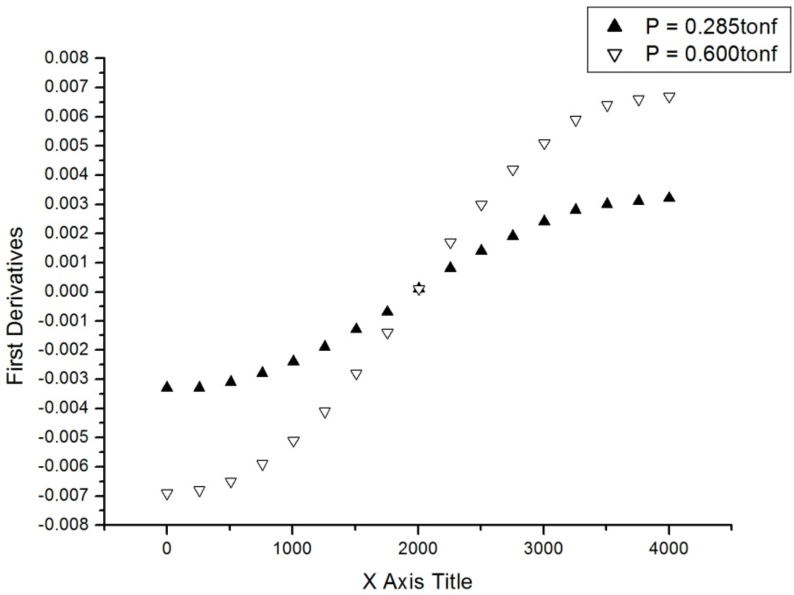

Fig. 5. Calculated First Derivatives using Four-Point Central Difference Method

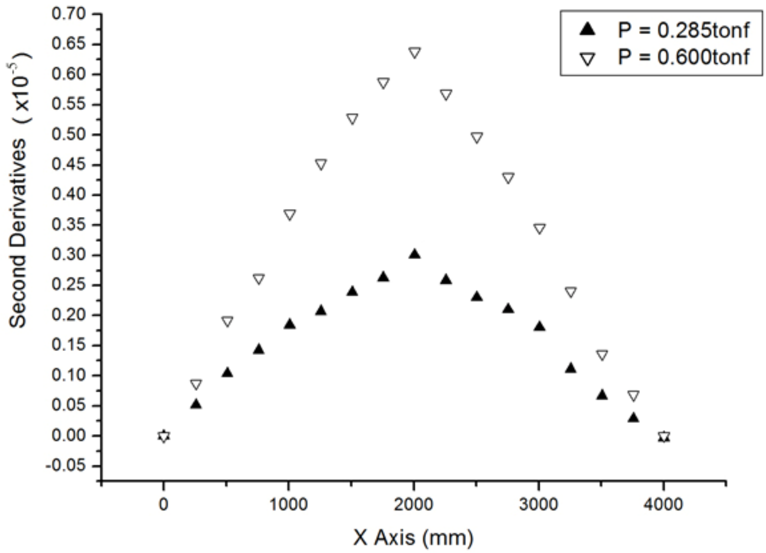

Fig. 6. Calculated Second Derivatives using Five-Point Central Difference Method

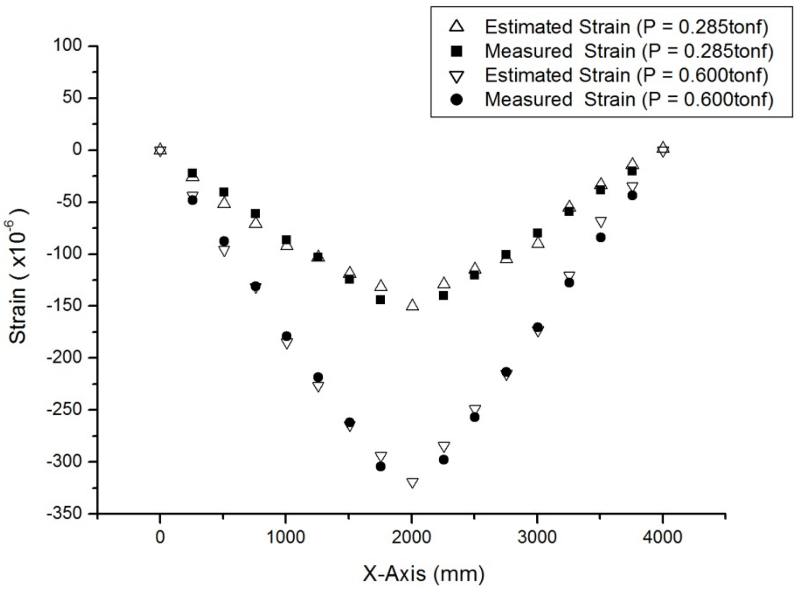

Fig. 7. Comparing with The Estimated Strain values from Measured by Strain Gages

Table 2. The Error between Estimated Strain values from measured by strain gages

X-axis (mm)	P = 0.285 tonf		P = 0.600 tonf	
	Absolute Error ($\times10^{-6}$)	Relative Error (%)	Absolute Error ($\times10^{-6}$)	Relative Error (%)
0.1	-	-	-	-
256.4	-3.511	15.811	4.627	-9.600
508.7	-11.422	28.280	-8.021	9.133
758.1	-9.930	16.246	-0.407	0.311
1007.0	-5.300	6.116	-5.551	3.099
1256.0	0.054	-0.052	-8.121	3.719
1506.9	5.327	-4.279	-2.482	0.948
1756.0	13.016	-9.015	10.657	-3.500
2007.4	-	-	-	-
2258.8	10.845	-7.746	13.672	-4.590
2504.7	5.910	-4.899	7.972	-3.106
2756.5	-4.404	4.382	-1.380	0.646
3007.7	-9.794	12.222	-2.497	1.463
3256.0	4.117	-6.926	7.475	-5.852
3506.4	5.046	-13.158	15.868	-18.900
3757.4	6.124	-29.994	9.268	-21.262
4002.9	-	-	-	-
Average	6.771×10^{-6}	11.366%	7.000×10^{-6}	6.152%

4 Conclusions

By comparing the Z-axis displacements measured by MCS from the data which was measured by LDS, the average absolute error was 0.2739mm and 0.2461mm for each case, and the average relative error was 8.08% and 4.91% for each case.

Also, by comparing the estimated strain values from the data obtained by strain gages, the average absolute error was 6.7715×10^{-6} and 6.9999×10^{-6} for each case, and and the average relative error was 11.37% and 6.15% for each case.

As a result of this, this proposed technique of estimating stress distribution was evaluated.

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