The Estimation Method of Stress Distribution for Beam Structures Using the Terrestrial Laser Scanning

Sang Wook Park, Jun Su Park, Byung Kwan Oh, Yousok Kim, Hyo Seon Park

Abstract—This study suggests the estimation method of stress distribution for the beam structures based on TLS (Terrestrial Laser Scanning). The main components of method are the creation of the lattices of raw data from TLS to satisfy the suitable condition and application of CSSI (Cubic Smoothing Spline Interpolation) for estimating stress distribution. Estimation of stress distribution for the structural member or the whole structure is one of the important factors for safety evaluation of the structure. Existing sensors which include ESG (Electric strain gauge) and LVDT (Linear Variable Differential Transformer) can be categorized as contact type sensor which should be installed on the structural members and also there are various limitations such as the need of separate space where the network cables are installed and the difficulty of access for sensor installation in real buildings. To overcome these problems inherent in the contact type sensors, TLS system of LiDAR (light detection and ranging), which can measure the displacement of a target in a long range without the influence of surrounding environment and also get the whole shape of the structure, has been applied to the field of structural health monitoring. The important characteristic of TLS measuring is a formation of point clouds which has many points including the local coordinate. Point clouds are not linear distribution but dispersed shape. Thus, to analyze point clouds, the interpolation is needed vitally. Through formation of averaged lattices and CSSI for the raw data, the method which can estimate the displacement of simple beam was developed. Also, the developed method can be extended to calculate the strain and finally applicable to estimate a stress distribution of a structural member. To verify the validity of the method, the loading test on a simple beam was conducted and TLS measured it. Through a comparison of the estimated stress and reference stress, the validity of the method is confirmed.

Keywords—Structural health monitoring, terrestrial laser scanning, estimation of stress distribution, coordinate transformation, cubic smoothing spline interpolation.

I. INTRODUCTION

FOR the safety of the structure under various load conditions such as wind, earthquake and unexpected loads, the maximum stress has been checked and assessed. If the maximum stress in the structural member exceeds the allowable stress, the member can lose its function in the structure. Thus, the stress can be the criterion for evaluating

Sang Wook Park, Jun Su Park, and Byung Kwan Oh are with the Architectural Engineering Department, University of Yonsei, Seoul, South Korea (e-mail: coolboysw@naver.com, park0487@naver.com, aeioobk@yonsei.ac.kr).

Yousok Kim is with the Center for Structural Health Care Technology in Buildings, University of Yonsei, South Korea (e-mail: yskim1220@yonsei.ac.kr).

Hyo Seon Park is with the Architectural Engineering Department, University of Yonsei, Seoul, South Korea (corresponding author to provide phone: +82-2-2123-2794; fax: +82-2-3408-3331; e-mail: hspark@yonsei.ac.kr).

safety of the structural member in structural health monitoring (SHM). For this, estimation of the maximum stress or stress distribution is required based on sensing. Hereupon, the researches which estimate the stress distribution of structure have been widely conducted using the contact sensor such as ESG (electric strain gauge), LVDT (Linear Variable Differential Transformer), VWSG (Vibrating Wire Strain Gauge) [1] and etc.

However, there exist various limitations such as the need of separate space where the network cables can be installed and the difficulty of access for the dangerous facility and the high-rise building. Therefore, non-contact sensors for overcoming the limits of contact sensors are being developed [2]. Among these, TLS (Terrestrial Laser Scanning) has begun to be used in civil engineering field as a non-contact sensor [3]. Since TLS was first introduced in GIS (Geographic Information System), it has been developed continuously and used for urban planning, land surveying and etc.

TLS has the system which can gain a three-dimensional coordinate using the laser pulse so it can measure the information of a target remotely. Dispersed laser comes back as reflected pulse from a target. Then, based on the locations of a target, the coordinate information can be acquired. Through the suggested method, it is possible to get information of the object without attachment of sensor. It means TLS is an alternative which can get over the limit of contact sensor. Thus, TLS can be utilized to estimate the response of a structural component of building and behavior of the structure based on measured deformation information.

According to advantage of TLS, this study suggests the estimation method which can estimate the deformed shape using the coordinate information from TLS and attempts to estimate the stress distribution of beam structure. The coordinate transformation of the data obtained by TLS, latticization of transformed data and CSSI (Cubic Smoothing Spline Interpolation) using the average point of each lattice are applied to the method for estimating the deformed shape in order. To verify the suggested estimation method, the loading tests for steel beam is performed. The deformed shape and stress distribution of steel beam are estimated from the measurements. Finally, stresses are estimated and compared with reference sensor.

II. STRESS ESTIMATION METHOD

TLS acquires the raw data which have dense interval to express the shape of a target. So, point clouds are formed by many points based on the local coordinate from TLS. It means that a coordinate transformation for the global coordinate is

needed to estimate the deformed shape. A generation of the base-vector is necessary for coordinate transformation because of measuring the displacement of the structure through the diffuse data. Thus, least squares approximation method which can reduce the errors is applied to the formation of each surface equation for flange and web of steel beam. Then, the base-vectors, O and E, are the intersection points which are generated from both endpoints of flange and lines intersecting between formed surface equations of flange and web. Over the base-vectors, parallel transformation and rotational transformation are carried out [4], [5].

Because transformed point clouds are distributed irregularly, to analyze quantitatively, linearization of the point is needed. Thus, lattices which have uniform interval R_{1,i_1} and R_{2,i_2} are formed to meet the compatibility condition for continuity. R_{1,i_1} and R_{2,i_2} mean the range conditions of each lattice for X-axis direction (the length of steel beam) based on global coordinate. i_1 refers to the each lattice number, where $i = 1, 2, 3, \cdots, m$. R_{1,i_1} forms the amount of m lattices in respect of the length from start point to end point. On the other hand, R_{2,i_2} forms the amount of $(m-1)$ lattices over the length from the middle point of first lattice for R_{1,i_1} to the middle point of last lattice for R_{1,i_1}. Each lattice calculates the mean value about their own data which is satisfied with the each range condition. Using the mean values for z-direction (Direction of vertical deflection) based on the global coordinate, the deformed shape can be determined. However, point clouds from TLS have the unexpected errors which can affect the tendency of deformed shape. Therefore, CSSI is needed to minimize the errors in the proposed method. CSSI as a type of the cubic spline interpolation can draw the tendency of data smoothly. When estimating the stress based on elastic curve method, the curvature is needed for calculating the strain. To find it, first and second order differential coefficient should be calculated. They can be calculated through two-point central difference and five-point central difference, respectively, in numerical differentiation using the interpolated data. Under the condition of the linear elastic modulus, the stresses are estimated using the formula, $\sigma = E \cdot \varepsilon$.

III. EXPERIMENT

To verify the validity of proposed method, the loading test was performed using the steel beam of $\mathrm{H}-100 \times 100 \times 6 \times 8$ subjected to point loads at the center. LDS as the reference sensor was used for confirming the displacement data from TLS and the installation locations of sensor was 0.5, 1.5, 2.0, 2.5, 3.5m, respectively. For comparison of the estimated stress values, ESG as the reference sensor was attached to the lower flange of steel beam at interval of 0.25m. Using the actuator which can control the displacement control the load was applied on the center of steel beam. Total 4 loading steps which

are made of initial test, 10mm, 15mm and 20mm displacement control were performed.
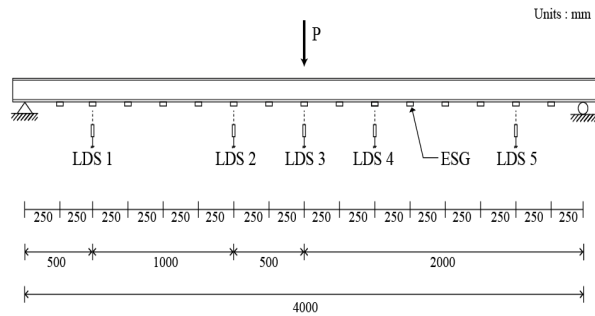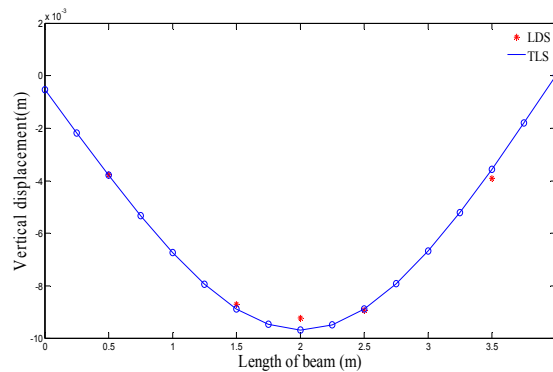

Fig. 1 Schematic diagram of the test model

Fig. 2 Deformed shape of the steel beam (Step 2)

TABLE I
DISPLACEMENT AND RELATIVE ERROR BETWEEN TLS AND LDS (STEP 2)

Location (m)	TLS(m)	LDS(m)	Relative error (%)
0.5	0.0038	0.0038	0.49
1.5	0.0089	0.0087	2.05
2.0	0.0097	0.0093	5.04
2.5	0.0089	0.0089	-0.45
3.5	0.0036	0.0039	-8.79

IV. RESULT

A. Displacement Estimation

As shown in the Table I, the verification result for estimated deformed shape shows the relative errors with maximum 8.79% (Step 2). On the location of 2.0m where the concentrated load was applied, the result is a relative error of 5.04%.

For step 3, the results are the relative errors within 5.82% except for location of 0.5m in Fig. 3. For step 4, similarly, the results are the relative errors within 6.83% except for location of 0.5m in Fig. 3. Especially, in the range of 1.5m to 2.5m, all steps are the relative errors with about 5%. Thus, applicability of estimated deformed shape for estimating the stress is examined.

B. Stress Estimation

Under the condition of the linear elastic modulus, the strain has proportionate relationship to stress. The value for the elastic modulus was gained by the specification of the steel beam. The

estimated displacements from the subsection *A* are used to calculate the differential coefficient.
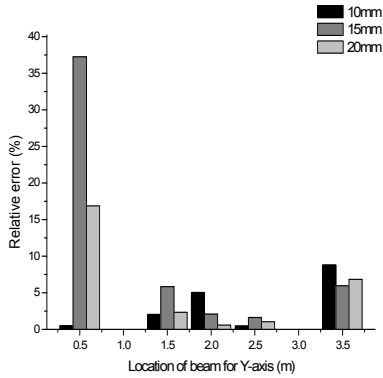

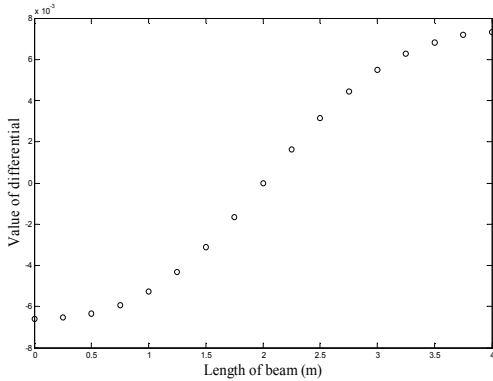Fig. 3 Relative error between TLS and LDS for estimated displacement (All cases)

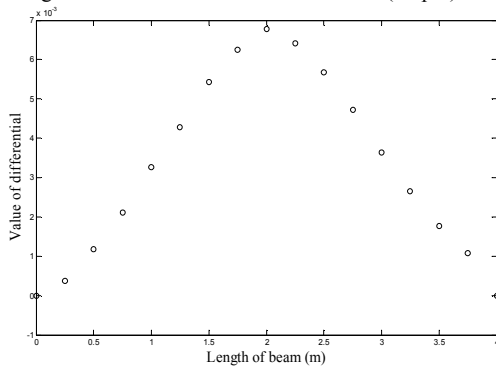Fig. 4 First-order differential coefficient (Step 2)

Fig. 5 Second-order differential coefficient (Step 2)

For Figs. 4 and 5, the results show the values of first and second order differential coefficient which use the two-point central difference and five-point central difference, respectively. The tendencies of them are symmetrical with center point as criterion.

Using the calculated coefficients, the curvature should be obtained for finding the strain because strain is proportional relation with stress based on the Hook's law. Because the strain

may be subjected to noise, the role of the CSSI method for revision of curvature is important.
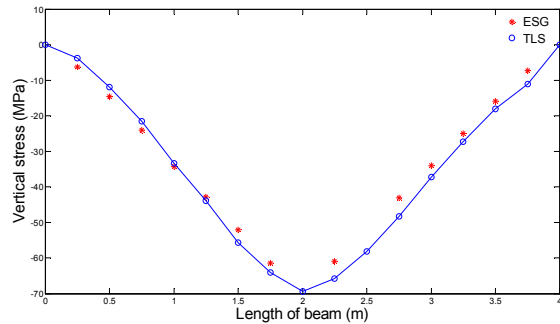

Fig. 6 Result of the estimated stress (Step2)

TABLE II
ESTIMATED STRESS AND RELATIVE ERROR BETWEEN TLS AND ESG (STEP 2)

Location	TLS(MPa)	ESG(MPa)	Relative error (%)
0.75	21.61	23.99	-9.89
1.00	33.36	34.23	-2.55
1.25	43.90	42.84	2.49
1.50	55.71	52.03	7.06
1.75	64.05	61.40	4.32
2.00	69.47	-	-
2.25	65.83	60.89	8.11
2.50	58.14	-	-
2.75	48.34	43.05	12.31
3.00	37.32	34.07	9.53
3.25	27.28	24.97	9.25

The stresses were estimated by applying the differential coefficient based on the numerical differentiation. The result is represented in Fig. 6. In Table II, the comparison results, between 1m and 3m, show the relative error with fewer than 10% except for one point. The blank means the unmeasured point.
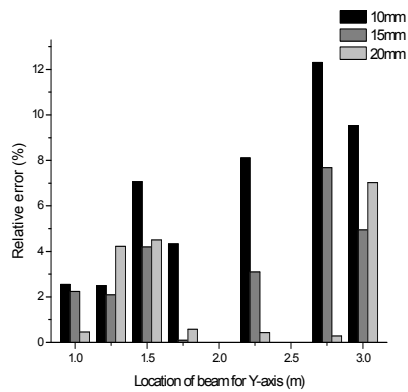

Fig. 7 Relative error between TLS and ESG for estimated stress (All cases)

In Fig. 7, the most error percentages show values below 10%. Although the largest load was applied to Step 3, the relative errors are less than 5%. According to the results, the validity of the suggested method is confirmed.

V. CONCLUSION

This study suggests the estimation method of stress distribution for steel beam using TLS. First of all, transformation of the raw data from TLS is needed to obtain the quantitative values for deflection of a target. Secondly, the lattices are formed at regular intervals for evaluating the representative value of each lattice. After that, CSSI is used to estimate the displacement and revise the curvature for strain. Finally, based on elastic curve method and Hook's law, the stress can be obtained. To verify the validity of the method, the loading test was performed using the steel beam. The obtained data from TLS were applied to the suggested method. It shows allowable relative errors for estimated displacement and stress. Therefore, application of TLS with the proposed method is valid to the assessment of SHM as a non-contact sensor.

ACKNOWLEDGMENT

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