Issues of shear deformation measurement in experimental studies

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Abstract. Shear deformation determined using “X configuration method” as traditional instrumentation plan is controversial. Shear deformation of two specimens was re-investigated in this research. One of those (SP3) was representing a RC beam member using a single curvature test scenario and a coupling beam specimen (CB2) was representing a RC beam member using double curvature test scenario. The new instrumentation technology, optical system, provides a useful tool to evaluate different traditional instrumentation plans. Shear deformation is evaluated with different gauge lengths. The best-possible solutions of both specimens are determined using the optical system with the finest grid. Error is estimated by comparing results from “X Configuration” method with the best-possible solution. Analysis results indicate that the smaller gauge length yields the better results. A gauge length of 6.3 in. (160 mm) from X configuration method gives the smallest error, less than 10 %, in measuring shear deformation in a flexural governed member. It suggests that the gauge length to measure shear deformation in a coupling beam specimen can be limited within 16.5 in. (420 mm). The largest gauge length from X configuration method in measuring shear deformation shows the largest error for both specimen SP3 and specimen CB2.

1. Introduction

An appropriate instrumentation plan is needed to measure shear deformation of the beam specimen. Traditional instrumentation system uses potentiometer or LVDT (Linier Variable Displacement Transducers) to determine shear deformation of the test specimen (Oesterle et. al, 1976). Both LVDT and potentiometer have certain length and weight which makes the installation process difficult and limits the number of instrumentations. It is not hard to find that different researchers has different layout of instrumentations depending on their engineering judgments.

Recently, thanks to the technology, the optical system that uses infrared signal to track the movements of “markers” in 3 dimensions has become increasingly popular. The marker, which is generally attached to the point of interest on the surface of the specimen, is relative small and can be handled easily. For example, the marker manufactured by Northern Digital Inc. Company has a diameter of 2.75 in. (7 mm) only. This use of optical system allows researchers to measure deformation of the specimens with denser instrumentation points. However, this system generally costs more than one hundred thousand U.S. dollars and is not affordable in many labs.
Traditional LVDT and potentiometer generally have larger gauge length compared to optical system. It raises a question whether those experimental results can be compared with each other. Considering that the optical system might be too expensive to be available for most of research labs, an acceptable installation plan using traditional instrumentations to minimize the error in measuring shear and flexural deformation becomes the main motivation of this research.

2. Methodology

Shear deformation of two specimens was re-investigated in this research. One of those (SP3) was representing a RC beam member using a single curvature test scenario (Nguyen, 2012) and a coupling beam specimen (CB2) was representing a RC beam member using double curvature test scenario (Lequesne, 2011; Setkit, 2012). The new instrumentation technology, optical system, provides a useful tool to evaluate different traditional instrumentations plans. Both specimens used optical system and have markers uniformly distributed in an approximately 6 in. grid attached on them, as shown in Figure 1. By tracking the positions of those markers with time, shear deformation can be calculated.

As shown in Figure 1, specimen SP3 and specimen CB2 have 28 and 45 markers attached on the specimen, respectively. The actual lateral displacement \( \Delta \) is defined as the relative movement between the first row markers and the top row markers. Based on the local coordinate system shown in Figure 3, the actual lateral displacement can be calculated using Eq. (1).

![Figure 1. Study example](image-url)
### Calculation of shear deformation

Calculating shear deformation requires shear strain. Shear deformation in a small quadrilateral element, as shown in Figure 2, can be determined based on the difference of the angles at two corners before and after deformation. Considering a quadrilateral element as shown in Figure 2, the element consists of 4 markers with original positions presented as the black shaded dots. When subjected to stresses, the four markers moved and the red solid line represents the distorted shape of the quadrilateral element after deformation. Markers 1, 2, 3, and 4 move to the new positions defined by their horizontal and vertical movements $u_1$, $u_2$, $u_3$, $u_4$ and $v_1$, $v_2$, $v_3$, $v_4$, respectively (Hines et al., 2002 and Dinh, 2009). So shear strain ($\gamma$) can be calculated by using Eq. (2). In which, $\alpha_1$ and $\alpha_2$ is defined positive clockwise and $\alpha_3$ and $\alpha_4$ is defined positive counter-clockwise. After shear strain is determined, shear deformation, $\Delta_y$, of each element can be calculated using shear strain multiplying by the element height, as shown in Eq. (3). It can be visualized by rotating the distorted element $\alpha_y$ degree clockwise, as shown in Figure 2. As can be seen in Figure 2, a positive shear strain, $\gamma$, moves the element to the right.

\[
\Delta = \frac{(x_{26} + x_{27} + x_{28}) - (x_1 + x_2 + x_3 + x_4)}{4} \tag{1}
\]

\[
\gamma = \frac{1}{2} (\alpha_1 + \alpha_2) + \frac{1}{2} (\alpha_3 + \alpha_4) \tag{2}
\]

\[
\Delta_y = \frac{1}{2} \left( \frac{u_1 - u_2}{\Delta y_{12}} + \frac{u_4 - u_3}{\Delta y_{34}} \right) + \frac{1}{2} \left( \frac{v_3 - v_2}{\Delta x_{23}} + \frac{v_4 - v_1}{\Delta x_{14}} \right) \tag{3}
\]

**Figure 2.** Deformation of a quadrilateral element  
(Dinh, 2009)
2.2. Formatting the text

Markers attached on specimen SP3 can be divided into six strips, as shown in Figure 3. Each strip had a height of 6.3 in. (160 mm) and comprised three quadrilateral elements. For the best-possible solution, shear strain was first evaluated within each cell using the “Angle Change” method, Eq. (2).

For the “X-Configuration” method, four scenarios are considered. First scenario uses the corner markers of each strip. This scenario simulates the use of 12 LVDTs with a vertical gauge length at approximately 6.3 in. (160 mm), as shown in Figure 3 (a). The second scenario simulates the use of 6 LVDTs with a vertical gauge length at approximately 12.6 in. (320 mm), as shown in Figure 3 (b). The third scenario simulates the use of 4 LVDTs with a vertical gauge length at approximately 18.9 in. (480 mm), as shown Figure 3 (c). And the fourth scenario simulates the use of 2 LVDTs with a vertical gauge length at approximately 37.8 in. (960 mm), as shown in Figure 3 (d).

Markers attached on specimen CB2 can be divided into seven strips, as shown in Figure 4. Each strip had a height of 5.5 in. (140 mm) and comprised four quadrilateral elements. For the best-possible solution, shear strain was evaluated within each cell using the “Angle Change” method, Eq. (2).

For the “X-Configuration” method, specimen CB2 was divided into two groups. Group 1 and group 2 consider two scenarios and four scenarios, respectively. As shown in Figure 4, first group used strip 1 to strip 7 and second group used strip 1 to strip 6 to evaluate shear deformation from the “X-configuration” method. First scenario of group 1 and group 2 use the corner markers of each strip. These scenarios simulate the use of 14 LVDTs and 12 LVDTs for group 1 and group 2, respectively, with a vertical gauge length at approximately 5.5 in. (140 mm), as shown in Figure 5. The second scenario of group 2 simulates the use of 6 LVDTs with a vertical gauge length at approximately 11 in. (280 mm), as shown in Figure 6 (a). The third scenario of group 2 simulates the use of 4 LVDTs with a vertical gauge length at approximately 16.5 in. (420 mm), as shown in Figure 6 (b). The second scenario for Group 1 and the fourth scenario for Group 2 simulate the use of 2 LVDTs with a vertical gauge length at approximately 38.5 in (980 mm) and 33 in. (840 mm) for group 1 and group 2, respectively, as shown from Figure 7.
Figure 3. Evaluating specimen SP3

Figure 4. Evaluating specimen CB2
Figure 5. 1st Scenario of specimen CB2

(a) Group 1

(b) Group 2

Figure 6. 2nd and 3rd scenario of specimen CB2

(a) 2nd Scenario

(b) 3rd Scenario
3. Result and discussion

3.1. Specimen SP3
The accumulated shear deformations from the 4 scenarios are compared with the best-possible solution, as presented in Figure 8. The error is estimated at each peak displacement and presented in Figure 9. As can be seen from Figure 9, except the 1st scenario, the errors for the other 3 scenarios are all significant throughout the test. It should be noted that Specimen SP3 has small shear deformation as the best-possible solution and thus a tiny difference causes significant error. Apparently, the 4th scenario with the vertical gauge length at 37.8 in. (960 mm) yields the worst results. The 1st scenario has error generally below 10%. However, it is very interesting to notice that the change of gauge length from 18.9 in. to 12.6 in. actually does not gain any advantage. Although analytical results from the 1st scenario seem acceptable, the trend of convergence is not convincing from the 4th scenario to the 1st scenario. Future research using a smaller grid of markers is needed to conduct the convergence study. Based on this example, it suggests that the gauge length to measure shear deformation in a flexural governed member should be limited within 6.3 in. (160 mm). The small gauge length is preferred because a small variation in shear deformation may cause significant error.

3.2. Specimen CB2
The accumulated shear deformations in group 1 and group 2 are compared with the best-possible solution, respectively, as presented in Figure 10 and 11. The error is estimated at each peak displacement and presented in Figure 12 and 13. The drift ratio on the horizontal axis is defined as the actual lateral displacement from 1st row to the top row markers divided by the average height in between. As can be seen in Figure 12 and 13, the error percentage tends to increase with increasing lateral drift. It is likely caused by out-of-plane movement at larger drift ratio due to concrete cover spall-off. Similar trend can be found also in Specimen SP3 in the previous example. Also, the trend of convergence of Specimen CB2 is more convincing than the Specimen SP3.
As expected, a gauge length of 5.5 in. (140 mm) from X configuration method provides the best solution. It seems results from a gauge length of 11 in. and 16.5 in. are also acceptable. However, the gauge length of 33 in. (840 mm) or 38.5 in. (980 mm) overestimates shear deformation by approximately 40% and 55% the most, respectively. Based on this example, it suggests that the gauge length to measure shear deformation in a coupling beam specimen can be limited within 16.5 in. (420 mm).

![Figure 8. Shear deformation comparison of specimen SP3](image)

![Figure 9. Shear error versus drift relationship of specimen SP3 at positive drift](image)
Figure 10. Shear deformation comparison of specimen CB2 (Group 1)

Figure 11. Shear deformation comparison of specimen CB2 (Group 2)
Figure 12. Shear error versus drift relationship of specimen CB2 (Group 1)

Figure 13. Shear error versus drift relationship of specimen CB2 (Group 2)
4. Conclusion
Shear deformation of two specimens was re-investigated in this research. From the analysis conducted in this research, the following conclusions can be drawn:
1. A gauge length of 6.3 in. (160 mm) from X configuration method gives the smallest error, less than 10%, in measuring shear deformation in a flexural governed member.
2. The change of gauge length to 12.6 in. (320 mm) and 18.9 in. (480 mm) of specimen SP3 does not gain any advantage.
3. A gauge length of 5.5 in. (140 mm) from X configuration method provides the best solution in measuring shear deformation of specimen CB2.
4. A gauge length of 11 in. (280 mm) and 16.5 in. (420 mm) seems acceptable in measuring shear deformation. It suggests that the gauge length to measure shear deformation in a coupling beam specimen can be limited within 16.5 in. (420 mm).
5. The use of 2 LVDTs from X configuration method in measuring shear deformation shows the largest error for both specimen SP3 and specimen CB2.

5. References
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