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STRENGTH INVESTIGATION OF SLIDING DOOR FRAME OF BUSWAY BY USING THREE ELEMENT ROSETTE STRAIN GAGE

Tono Sukarnoto, Supriyadi, Sigit Subiantoro and Soeharsono
Department of Mechanical Engineering, Trisakti University, Jakarta, Indonesia
E-Mail: gatotsoeharsono@yahoo.com

ABSTRACT

City bus, namely busway was being popular in Jakarta. In several busway fleets, there are sliding doors that have large dimension that can inhibit the mobility of passenger. However, a new model of this door has been redesigned. The dimension of new design was the same as the dimension of the existing system i.e., 1800 mm height x 900 mm width but using square pipe 50 x 25 mm instead of using 60 x 30 mm square pipe as door frame. The strength of the new model was tested using Finite Element Method and showed that new door was strong enough to withstand the load. However, the strength should be investigated further experimentally. In this research, the experimental investigation of the strength of new sliding doors model were discusses. The model of the door was made from structural steel with minimal yield strength 175 MPa. The model was placed horizontally and supported in each corner of the door. A mass of 50 kg were loaded in the middle of the door. Three elements rosette strain gage were used as transducer and located in the critical point of the door. The strains were recorded using precision data Logger and von Misses stress was calculated. The result showed that the new design was strong enough to withstand the load.

Keyword: busway, redesign of sliding door, three element rosette strain gage, von misses stress.

INTRODUCTION

Now days, City buses, namely busway (BW) was being popular in Jakarta and used as Bus Rapid Transport (BRT). In several BW fleet, there are sliding doors that have large dimension. This door and its door housing needed much space inside the bus. This condition can inhibit the mobility of passenger. However, this sliding should be redesigned.

Tono *et al*. (2011) and Tono *et al*. (2012) was conducted a new design of sliding door to replace the existing sliding door (Figure-1). The dimension of new design was the same as the dimension of the existing system 1800 mm height x 900 mm width but using square pipe 50 x 25 mm (thickness = 2 mm) instead of using 60 x 30 mm (thickness = 2 mm) square pipe as door frame. This pipe was structural steel with yield strength of about 175 MPa. The strength of the new model was simulated by using Finite Element Method. The model was simply supported at each corner and subjected a distributed load about 500 N at the middle of the door. Simulation result is shown in Figure-2. Maximum von Misses stress about 56 MPa were found. This result showed that new door was strong enough to withstand the load. To insure that the new design is strength enough to withstand the load, however, the strength should be investigated further experimentally.

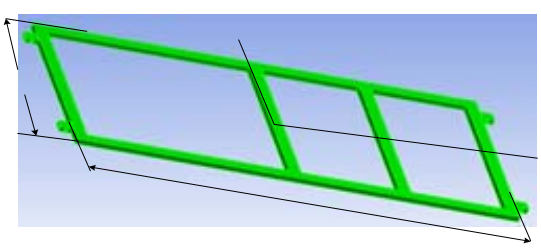

Figure-1. New design of sliding door frame.

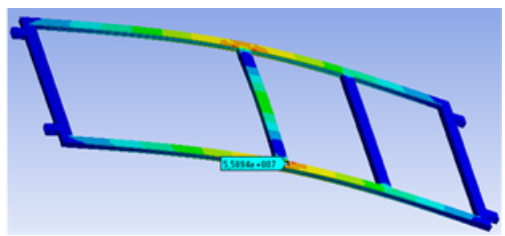

Figure-2. Simulation result using finite element method.

Rosette Strain-gage is probably the most common method for strain measurement on experimental stress analysis utilized by many industrial and scientific applications as well (Adewuyi *et al*., 2009; Soeharsono *et al*., 2009; Younis *et al*., 2011). The equation used on rosette strain-gage is primarily based on elasticity equation, particularly equation of strain transformation (Dally *et al*., 1991; Budynas, 1999). Consider rosette strain gage in Figure-3. A, B and C are strain gage and θ_A, θ_B and θ_C are gage orientation to x axis, respectively. According to strain transformation formula:

$$\epsilon_A = \epsilon_x \cos^2\theta_A + \epsilon_y \sin^2\theta_A + \gamma_{xy}\sin 2\theta_A$$
$$\epsilon_B = \epsilon_x \cos^2\theta_B + \epsilon_y \sin^2\theta_B + \gamma_{xy}\sin 2\theta_B$$
$$\epsilon_c = \epsilon_x \cos^2\theta_C + \epsilon_y \sin^2\theta_C + \gamma_{xy}\sin 2\theta_C \quad (1)$$

In case the orientation of strain gages A, B and C is set to $0^0, 45^0$ and 90^0 to x axis, the strain can be simplified as:

$$\epsilon_A = \epsilon_x$$
$$\epsilon_B = \frac{(\epsilon_x + \epsilon_y)}{2} + \gamma_{xy}$$
$$\epsilon_c = \epsilon_y \quad (2)$$

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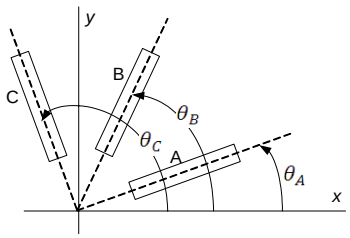

Figure-3. Three-element rosette strain gage.

Equation (1) and equation (2), combining with stress-strain relation are used to determine stress and strain in any orientation, also used to determine principle stress and strain and their orientation so that the von Misses stress can also be determine.

This research concerned with experimental investigation of the new design sliding door frame experimentally. The objective of this research is to insure that the new sliding door is strong enough to withstand the load so that the passenger in the BW is safely from the danger caused by the weakness of the door.

MATERIAL AND METHOD

Experimental setup

To investigate the strength of the new sliding door frame, a statics test was conducted in Engineering Mechanics Laboratory, Mechanical Engineering Department of Trisakti University. The sliding door frame to be test was base on the new design as shown in Figure-1. Experiment setup is shown in Figure-4. The sliding door frame was set horizontally and simply supported at four corners, namely at point K, L, M and point N. X and Y coordinates were chosen as shown in Figure-1. Seven-three rosette strain gages (gage A, B, C, D, E, F and G) were used as strain transducer. Gage A, B and gage C were located at lower-left side of the door, Gage D, E and gage F were located at lower-right side of the door while gage G was located at the center-lower side of the door (Figure-5). Gage A, C, D, and gage F were 5 cm apart from Y center line of the door. For convenience, each three rosette strain gage was oriented in X, Y and XY direction. For example A_x is the first A gage with X orientation, A_y is the third A gage with Y orientation while A_{xy} is the second A gage with 45^0 orientation to X axis. A ten channel precision data logger was used as strain measurement.

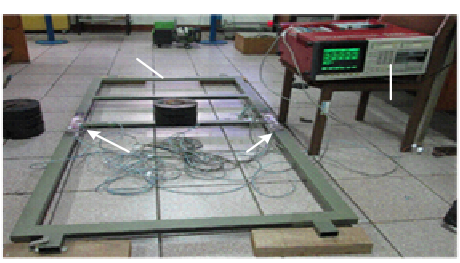

Figure-4. Experiment setup.

Figure-5. Installation of strain gage.

Due to limited channel on the data logger, the experiments were divided in three stages. In the first stage, the stress at gages A, B and C were test following test at gages D, E and F while in the last stage, the stress in gage G was test. In each stage, the door was loaded vertically at point G. The loading was 0 to 50 g N and 50 g to 0 N and the strain data were recorded by data logger.

Data analysis

To avoid error were caused by strain transfer sensitivity or if the transverse sensitivity of the gage elements in the rosette is other than zero, the individual strain readings will be in error, and the principal strains and stresses calculated from these data will also be incorrect. In that case, the effects of transverse sensitivity should always be considered in the data analysis of a biaxial stress field with rosette strain gages (Vishay Precision Group, 2010b; Budynas, 1999; Warren *et al*., 2002).

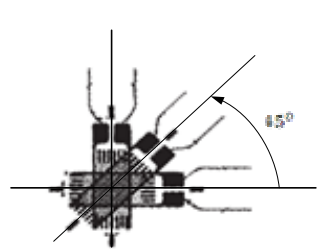

Figure-6. Three elements rosette strain gage.

Considered three-element rosette strain gage shown in Figure-6. In this case, strain gage A is oriented to x-axis. Assumed that:

$\hat{\epsilon}_A, \hat{\epsilon}_B, \hat{\epsilon}_C$: measured strain by data logger on gage A, B and gage C

$\epsilon_A, \epsilon_B, \epsilon_C$: corrected strain of gage A, B and gage C.

K_t, μ_0 : transfer sensitivity factor and poison ratio of the gage.

The formula for strain correction is:

$$\epsilon_A = \epsilon_x = \frac{1-\mu_0 K_t}{1-K_t^2}(\hat{\epsilon}_A - K_t\hat{\epsilon}_C)$$

$$\epsilon_B = \frac{1-\mu_0 K_t}{1-K_t^2}(\hat{\epsilon}_B - K_t(\hat{\epsilon}_A + \hat{\epsilon}_B - \hat{\epsilon}_C)) \qquad (3)$$

$$\epsilon_C = \epsilon_y = \frac{1-\mu_0 K_t}{1-K_t^2}(\hat{\epsilon}_C - K_t\hat{\epsilon}_A)$$

$$\gamma_{xy} = 2\epsilon_B - (\epsilon_A + \epsilon_C)$$

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Principle strain, principle stress and von Misses stress following the equation:

$$\epsilon_1 = \frac{\epsilon_x + \epsilon_y}{2} + \left(\left(\frac{\epsilon_x - \epsilon_y}{2}\right)^2 + \gamma_{xy}^2\right)^{0.5}$$

$$\epsilon_2 = \frac{\epsilon_x + \epsilon_y}{2} - \left(\left(\frac{\epsilon_x - \epsilon_y}{2}\right)^2 + \gamma_{xy}^2\right)^{0.5} \quad (4)$$

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\end{Bmatrix} = \begin{bmatrix}1 & \mu\\ \mu & 1\end{bmatrix}\begin{Bmatrix}\epsilon_1\\ \epsilon_2\end{Bmatrix} \quad (5)$$

$$\sigma_{VM} = (\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2)^{0.5} \quad (6)$$

RESULT AND DISCUSSIONS

Strain correction was calculated based on equation (3) and the result are shown in Table-1. Measured strains (mean of ten times measurement) were denoted by $\hat{\epsilon}_A$, $\hat{\epsilon}_B$ and $\hat{\epsilon}_C$ while corrected strains were denoted by ϵ_A, ϵ_B and ϵ_C.

Table-1. measured and corrected strain at point B.

Applied load (N)	**Measured strain** (μs)			**Corrected strain** (μs)		
	$\hat{\epsilon}_A$	$\hat{\epsilon}_B$	$\hat{\epsilon}_C$	ϵ_A	ϵ_B	ϵ_C
0	0	0	0	0	0	0
98.1	124	33	-34	125	27	-45
196.2	247	70	-68	249	58	-91
294.3	377	111	-100	380	93	-135
392.4	496	147	-135	500	123	-182
490.5	620	184	-170	625	154	-228

Table-1 shows that strain correction factor was greatly influenced to measured strain. For example in the load of 490.5 N, transfers sensitivity factor was converted measured strain in y direction from $\hat{\epsilon}_C = -170\ \mu s$ to true strain $\epsilon_C = -228\ \mu s$, the difference is about 35%. However, transfer sensitivity factor should be included in stress analysis.

Due to symmetries location of strain gage, there were slightly different between measured strains on symmetrical point. Thus, analysis will be limited to stress at point A, B and stress at point G.

Table-2. Principle stress at point A, B and G.

Load (N)	**Principle stress point A** (Mpa)		**Principle stress point B** (MPa)		**Principle stress point G** (MPa)	
	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2
0.0	0.00	0.00	0.0	0.00	0.00	0.00
98.1	22.64	-3.41	23.0	-4.48	14.61	-2.60
196.2	43.52	-5.67	48.5	-7.00	28.76	-4.72
294.3	65.90	-7.11	72.2	-11.48	41.37	-5.40
392.4	86.50	-9.90	95.0	-15.30	58.01	-7.39
490.5	107.21	-9.90	118.4	-18.76	72.36	-8.96

The principle stress was calculated based on equation (5) and the result at point A, B and G is shown in Table-2. In the load of 490 N, the maximum principle stress was occurred at point B that is $\sigma_1 = 118.4$ MPa and $\sigma_2 = -18.8$ MPa and the maximum shear stress was $\tau_{max} = \frac{(\sigma_1 - \sigma_2)}{2} = \frac{137.2}{2}\ MPa.$ Tresca failure theory for ductile material states that yielding will occur when the maximum shear stress reaches to yielding of material or $\tau_{max} = \frac{(\sigma_1 - \sigma_2)}{2} > \frac{\sigma_y}{2}$. Experiment results showed $(\sigma_1 - \sigma_2) = 137.2\ MPa$ while yielding strength of material is 175 MPa. This result showed that the new door frame is strong enough to withstand vertical load at point G up to 492 N.

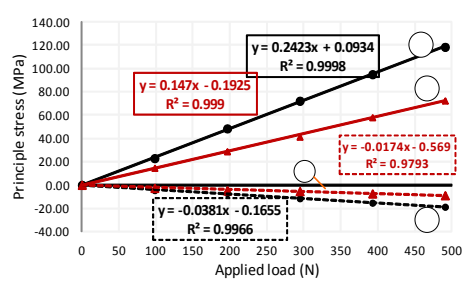

Figure-7. Graph of principle stress at point B and G, 1: σ_1 at point B, 2: σ_2 at point B, 3: σ_1 at point G, 4: σ_2 at point G.

Graph of principle stress at point B and G is shown in Figure-7. Simplicity the principle stress at point B yield:

$\sigma_1 = 0.2423\ F_z\ \sigma_2 = -0.0381\ F_z$,

And $\sigma_1 - \sigma_2 = 0.2804\ F_z$ (7)

Where F_z is vertical force that applied at point B. While yielding strength of material is about 175 MPa, according to Tresca theory, the maximum vertical force that can be retained by new door frame is:

$$F_z = \frac{175}{0.2804} = 620\ MPa$$

Table-3. Von Misses stress at point A, B and G.

Applied load (N)	**Von Misses stress** (MPa)		
	Point A	**Point B**	**Point C**
0.00	0.00	0.00	0.00
98.10	24.52	25.57	16.06
196.20	46.61	50.94	31.39
294.30	69.73	77.34	44.32
392.40	91.85	102.11	62.03
490.50	113.84	127.57	77.23

Von Misses stress was calculated based on equation (6) and this stress at point A, B and G is shown in Table-3 while comparison of von Misses stress at point A, B and G is presented in Figure-8. The highest von Misses stress caused by vertical load at point G was 127.57 MPa, occurred at point B at vertical load of 490 N. This stress is lower then yielding strength of door frame material (175 MPa). According to maximum energy distortion failure theories, this von Misses stress obviously proved that the door frame will not yielding if the door frame subjected to vertical force at point B up to 490 N.

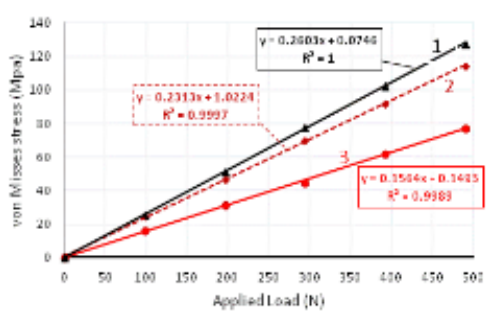

Figure-8. Von Misses stress at point A, B and D, 1: σ_{VM} at point A, 2: σ_{VM} at point B, 3: σ_{VM} at point G.

The equation of von Misses stress at point B in Figure-8 graph 1 can be simplified as $\sigma_{VM} = 0.2603\ F_z$. While yielding strength of material is about 175 MPa, according to maximum energy distortion theory, the maximum vertical force that can be retained by new door frame is:

$$F_z = \frac{175}{0.2603} = 672\ MPa$$

CONCLUSIONS

The above discussion can be concluded as:

a) According to Tresca (maximum shear stress) theory and maximum distortion energy theory, the new door frame was strong enough to retained perpendicular load subjected at the center of the door frame up to 490 N.
b) According to Tresca theory, the new door frame is still strong enough; even the vertical load is increasing up to 620 N.
c) According to maximum distortion energy theory, the new door frame is still strong enough; even the vertical load is increasing up to 670 N.

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