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Methods for Investigate and Resolving Shear-Induced Wall Cracks

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Abstract Over time, buildings undergo damage influenced by various factors. This vulnerability spans the entire lifespan of buildings, starting from the initial planning and implementation stages. A common consequence is damage to architectural components, particularly the formation of cracked walls. PU Ministerial Decree number 16/PRT/M/2010 identifies multiple factors contributing to wall cracks, including plaster layer expansion and shrinkage, vibrations from traffic, seismic events, and structural deformation. This research was carried out by making a wall construction prototype. The prototype will be given pressure as a lateral load so that the wall construction cracks. Test results indicate a deflection of 75 mm at a 498 kg load for a steel structure frame without brick masonry. Conversely, a frame structure with brick masonry showed a deflection of 27 mm. This comparison reveals the potential of brick wall pairs as stiffeners in steel structure frame construction. However, a cautionary note emphasizes that stronger brick walls may expedite the collapse of the structure by exerting pressure on steel columns, originally designed for tensile forces but experiencing bending forces when pressed against the bricks. Analyzing the test results and repairing techniques' efficiency underscores the reinforcement of walls as the most effective approach to addressing structural cracks due to shear collapse. This method withstands a lateral load of 581 kg, with an associated implementation cost of Rp. 293,125.00.

Keyword Masonry, Innovative Repair, Inspection, Prototype

1. Introduction

A building comprises architectural, structural, and mechanical components, functioning as a space for human activities. Maintaining the reliability of a building is crucial for its ongoing functionality. Over time, building components may undergo damage due to various factors. Aditya [1] notes that damage is likely from the planning and implementation stages until the end of a building's useful life. Cracked walls are a common manifestation of damage to architectural components, as highlighted by PU Ministerial Decree number 16/PRT/M/2010, which attributes such cracks to factors like plaster layer expansion, traffic vibrations, earthquakes, and structural deformation [2]. Cracks in buildings are a universal problem faced all over the world. Building components will develop cracks if the stress on the component exceeds its strength. Stress in building components can be caused by externally applied forces such as dead, live, wind, earthquake loads, or foundation settlement, or it can be internally caused due to temperature variations, humidity changes, and chemical action. Cracks affect the artistic appearance of the building, damage the integrity of the walls, affect the safety of the structure, and even reduce its durability [3]

According to Scofi tech, cracks in the walls not only spoil the beauty of the house, but can also be a source of disaster if left unchecked. Cracks can widen, damage the paint layer, damage other parts of the house (windows, roof, etc.), and possibly collapse. To prevent the cracks from getting worse, of course, they must be repaired. We need to recognize the cause so that repairs can be made as needed [4]. Walls, typically non-structural components, can also serve as structural elements, supporting loads such as basement walls and shear walls. The National Disaster Management Agency stated that the damage caused by the natural disaster was on the roof, columns, beams, walls and floors, while the biggest damage was on the walls made of bricks [5]. And according to Junior [6], factors contributing to wall damage include climate influences, earthquakes, material composition, construction technology, and maintenance. The prevalent damages to walls involve peeling, cracks, and mossy plaster, as specified by PU Ministerial Decree number 16/PRT/M/2010, including hairline cracks, cracks, and fissures [2]. Parameter results are obtained from laboratory test results. The direction of the cracks starts from the exposed then goes to the weak area. The weak area is located at the mortar joint with the brick wall [7].

To repair brick walls, reference [8] recommends careful examination through periodic, initial, and follow-up inspections, using visual checks or ultrasonic detection equipment. Repair methods involve shotcrete, dry packing with a Portland cement aggregate mix, or mortar and epoxy injection. Strengthening brick walls can be achieved through prestressing or adding reinforcement to the surface, as suggested by [9]. With the preliminary building inspection method according to Pd-T-11-2004-C [10]. So it is necessary to develop a type of reinforcement from within such as internal reinforcement in red masonry that does not change the shape, visualization, can be used for all types of buildings, and can also increase the strength of the building, namely interlocking reinforcement of red masonry. Interlocking masonry reinforcement is a reinforced red brick where the material is installed in the middle of the brick with the aim that bricks like this have a lock between one brick and another brick. With the reinforcement installed in the middle of the brick, the brick will be connected to each other in the structural part of each brick with the reinforcement installed in this part of the brick, so as to increase the shear strength and not easily damaged [11].

Dynamic analyses by Salim [12], Syifa [13] in Malang city and shear force analysis by Yanno [14] highlight the vulnerability of masonry walls to lateral loads. Masonry walls, with a tensile strength of 1.5-2.0% of their compressive strength, are prone to cracking and destruction [15]. Consequently, research is necessary to identify suitable repair techniques for wall damage caused by lateral forces. The research aims to determine the characteristics of brick construction with a weak column structure against shear failure and identify the most effective repair technique for addressing cracks in walls resulting from shear failure.

2. Method

The method used in this research is an experimental method, namely making a prototype wall construction using a steel frame and brick masonry, then the wall construction is pressured from the side using hydraulic jacks as a lateral force to determine the strength of the wall construction before and after repairs are carried out. The research stages are as follows:

2.1. Wall Construction Inspection

a. Calculation of the Strength of Steel Frame Structures Against Tensile Strength

Yield strength material

$$\phi T_n \leq \phi A_g f_y \quad (1)$$

Strength of fracture

$$\phi T_n \leq \phi A_e f_u \quad (2)$$

Nominal Compressive Strength

$$\phi P_n = 0.9 F_{cr} A_g \quad (3)$$

Strength of Bolts (Shear Strength)

$$\phi R_n = m r_1 F_{ub} A_b \quad (4)$$

b. Lateral Strength Testing of Steel Frame Structures

c. Visual Inspection

2.2. Analysis of Repair Techniques

The method of repairing wall damage is chosen according to the cracks that occur. Improvements to building components basically aim to increase strength and ductility. To achieve one of the strengthening objectives, various materials and construction methods can be used as shown in Figure 1.

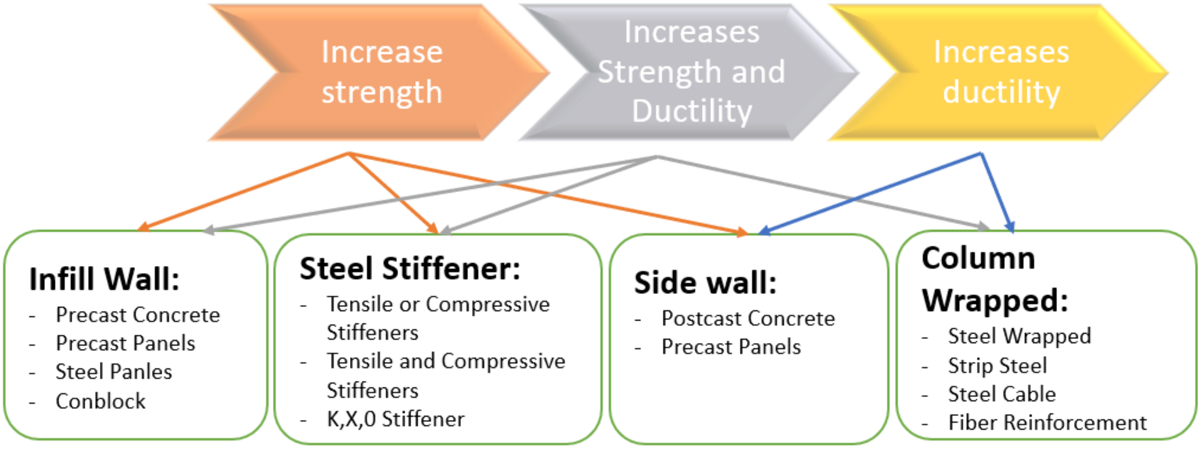


Figure 1. Strengthening Techniques

3. Results and Discussion

In this research, a prototype of a wall pair with an angled steel frame was created as a test object for lateral force testing. The prototype design uses angle steel profiles to determine the characteristics of wall pairs due to shear failure. The wall construction prototype design can be seen in Figure 2.

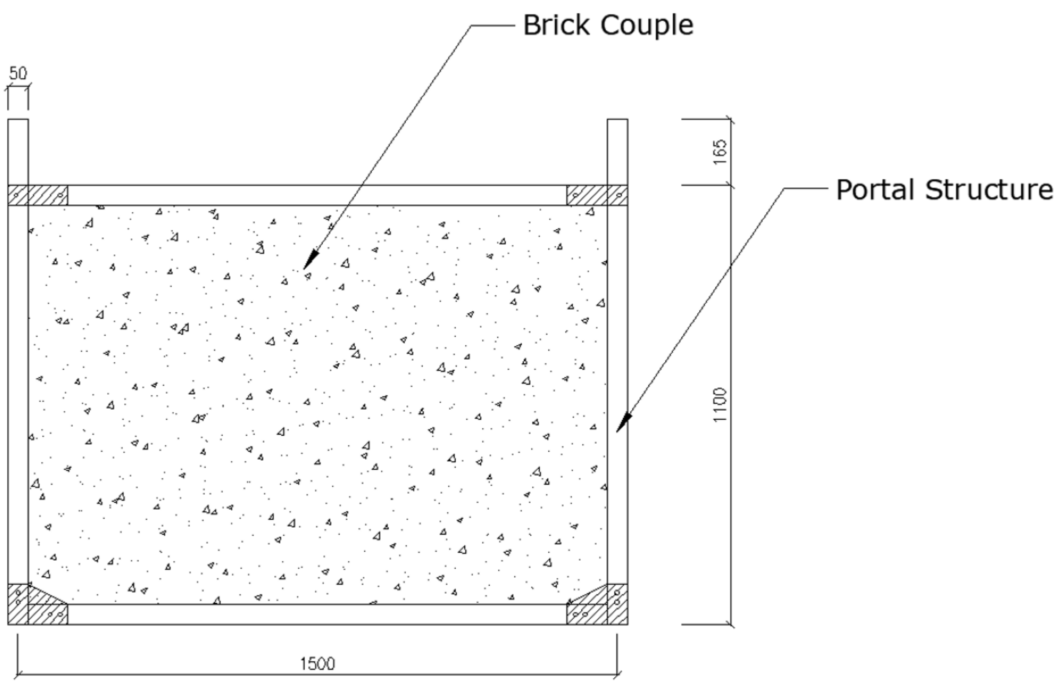


Figure 2. Wall Construction Prototype Design

3.1. Wall Construction Inspection

3.1.1. Calculation of the Strength of Steel Frame Structures

The steel frame structure used in wall construction is 60 mm x 60 mm x 5 mm angle profile steel with BJ-37 steel quality and is connected using 2 bolts with a diameter of 10 mm. The strength of the frame structure is as follows:

Against Tensile Strength

Analysis of yield strength material using equation (1). The analysis is as follows:

$$\phi T_n \leq \phi A_g f_y$$

$$\phi T_n = 0,9 \times 631 \times 240$$

$$\phi T_n = 136296 \ \ N = 1389,38 \ \ kg$$

Based on the calculation results, the material's yield strength value is obtained as 1389,38 kg.

The analysis of strength of fracture is conducted using equations (2). The analysis is as follows:

$$\phi T_n \leq \phi A_e f_u$$

$$\phi T_n = 0.75 \times 413,95 \times 370$$

$$\phi T_n = 114871,1 \ \ \text{N} = 11713,64 \ \ \text{kg}$$

Based on the calculation results, the strength of fracture value is obtained as 11713,64 kg. Considering the materials yield strength and strength of fracture value, it can be conclude that the steel frame structure 60 mm x 60 mm x 5 mm elbow profile is able to withstand a tensile strength of 11713,64 kg.

Compressive Strength

Single elbow compression structural component

$$\frac{b}{t} = \frac{60}{6} = 10 < 0,71\sqrt{\frac{E}{F_y}} = 20,49$$

Based on the calculation results, torsional bending does not need to be considered.

Calculation the ratio of L/r_a

$$\frac{L}{r_a} = \frac{1000}{18,2} = 54,94 < 80$$

Analysis *KL/r*

Because $L/r_a \leq 80$, so the equation is used:

$$\frac{L_c}{r} = 72 + 0,75\frac{L}{r_a}$$

$$\frac{L_c}{r} = 72 + 0,75 \times 54,94 = 113,208$$

Analysis value of $4,71\sqrt{\frac{E}{F_y}} = 4,71\sqrt{\frac{200.000}{240}} = 135,966$

Calculated critical stress, because $L_c/r < 4,71\sqrt{E/F_y}$, so the equation is used:

$$F_{cr} = \left(0,658^{\frac{F_y}{F_e}}\right) F_y$$

$$F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2}$$

$$F_e = \frac{\pi^2 \times 200.000}{\left(113,208\right)^2} = 153,861 \ \ \text{MPa}$$

$$F_{cr} = \left(0,658^{\frac{240}{153,861}}\right) 240 = 124,931 \ \ \text{MPa}$$

Analysis nominal compressive strength with equation (3).

$$\phi P_n = 0.9 \times 124,931 \times 631 = 70948,44 \ \ \text{N} = 7234,755 \ \ \text{kg}$$

Based on the calculation results, the steel frame structure 60 mm x 60 mm x 5 mm elbow profile is able to withstand a compressive strength of 7234,755 kg.

Strength of Bolt

Shear strength of bolt is calculated using an equation (4).

$$\phi R_n = 0,75 \times 1 \times 0,5 \times 825 \times 78,5 = 24285,94 \ \ \text{N} = 2476,486 \ \ \text{kg}$$

Support strength of bolt

The design support strength depends on the weakest part of the bolt or plate.

Two or more bolts in the direction of force: $s \geq 3d$ and $Le \geq 1,5d$, so

$$\phi R_n = \varphi_f \times R_n = 2,4 \times \varphi_f \times d_b \times t_p \times f_u$$

$$\phi R_n = 2,4 \times 0,75 \times 10 \times 6 \times 370 = 39960 \ \ \text{N} = 4074,801 \ \ \text{kg}$$

A load of 2476.486 kg can be supported by a single 10mm diameter bolt. In the prototype design, which incorporates two bolts, the total load capacity becomes 4952.971 kg (2476.486 kg x 2). The strength analysis of the steel frame structure, utilizing a 60.60.6 mm angle steel profile, confirms that the frame is indeed capable of withstanding the calculated load of 4952.971 kg.

3.1.2. Lateral Force Testing of Steel Frame Structures

Without Masonry

The first examination conducted involves conducting a lateral load test on the steel frame structure without masonry, to determine the behavior of the steel frame structure in receiving lateral load. The steel frame can be seen in Figure 3 and the loading test in Table 1.

Figure 3. Testing of Steel Frames without Masonry

Table 1. Lateral Load Tests Results on Steel Structure Frames (Without Masonry)

Test	Load (kilogram)	Deformation (millimeter)	Crack (millimeter)
1	83		
2	166		
3	249		
4	332		
5	415		
6	498	75	
7	581	79	
8	664	80	
9	748	80	
10	831	81,3	
11	914	82	
12	997	82	
13	1080	83	
14	1163	83	
15	1246	83,5	
16	1329	84	BOLT FAILURE
17	1063	85	

Table 1 is the result of lateral load testing on steel frames structure without masonry. It can be seen that in the 16th test with a load of 1329 kg the bolts in the steel structural frame connections broke, while Figure 4 is a graph of Table 1 data.

Based on the results of lateral load testing for a steel frame without masonry, it can be seen that it has a strength of 1063 kg (with a deflection of 85 mm).

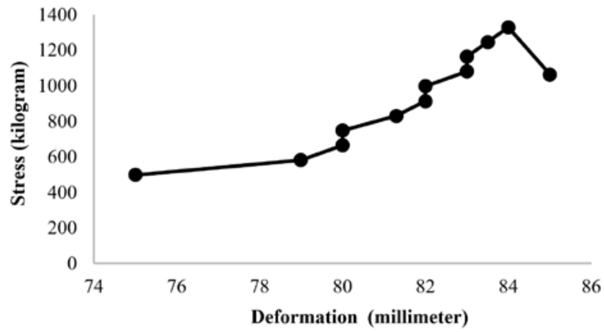


Figure 4. Graph of the Stress and Strain Relationship of Steel Structure Frames (Without Brickwork)

With Masonry

The next inspection is to carry out lateral load testing on steel structural frames with brick masonry to determine the behavior of steel structure frames with brick masonry in receiving lateral loads. Lateral Load Test Results on Steel Structure Frames can be seen in Table 2 and Figure 5.

Table 2 is the result of lateral load testing on steel frames structure with masonry. It can be seen that in the 5th test with a load of 415, cracks began to appear on the wall and experienced a deformation of 21mm. Figure 5 is a graph of Table 2 data.

Table 2. Lateral Load Test Results on Steel Structure Frames (with Bricks)

Test	Load (kilogram)	Deformation (millimeter)	Crack (millimeter)
1	83	6	
2	166	10	
3	249	13	
4	332	16	
5	415	21	Wall Cracks
6	498	27	Partially Destroyed
7	316	84	

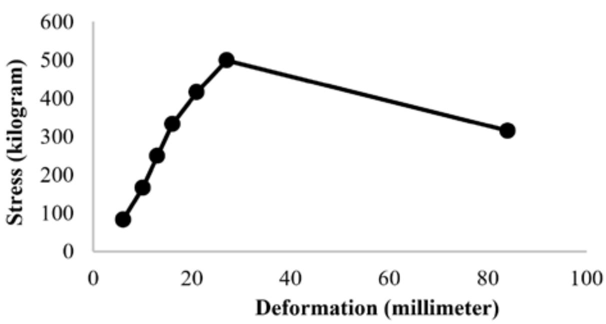


Figure 5. Graph of the Stress and Strain Relationship of Steel Structure Frames

Based on the results of lateral load testing for a steel frame with brick masonry, it can be seen that it has a strength of 498 kg with a deflection of 27mm. From the test data it can also be seen that at a load of 415 kg the wall pairs begin to crack, and at a load of 498 kg some of them are destroyed.

The test results at a load of 498 kg for a steel structure frame without masonry resulted in a deflection of 75mm, while for a frame structure with masonry there was a deflection of 27mm. Based on the comparison of these data, it can be seen that masonry walls can act as stiffeners in steel structure frame construction.

The test results can also be seen that the steel structure frame without brick masonry has a strength of 1329 kg, while the steel structure frame with brick masonry has a smaller strength, namely 498 kg, this can happen because the brick masonry is stronger than the steel structure frame construction, so the masonry pushes the steel column which should receive a tensile force due to lateral force, but instead receives a bending force when the masonry is pushed, this causes the steel profile to bend and accelerates to the breaking point.

3.1.3. Visual Inspection

After testing the lateral load on the wall components, an inspection is then carried out to determine the type of damage. The result of the examination can be seen in figure 6.

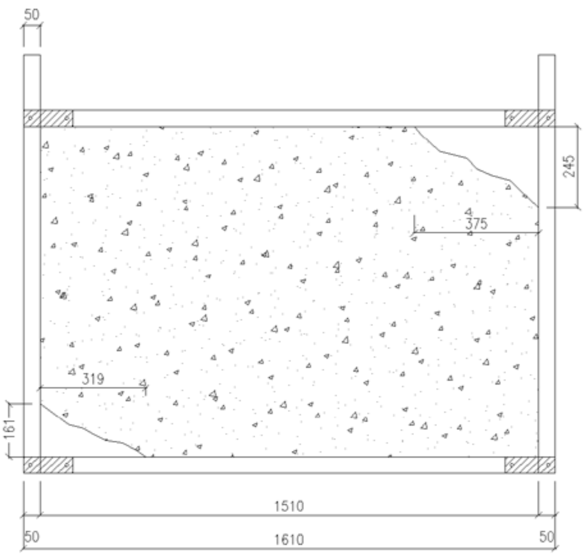


Figure 6. Results of inspection of damage to wall components

3.1.4. Analysis of Repair Techniques

Based on the results of the inspection of damage to the structure and masonry, repairs can be made to steel column components that are buckling and also repair cracks in the masonry.

Strengthening Technique with Plate Stiffener

One way to strengthen a steel profile that is experiencing bending is by adding a stiffener plate to the part that receives the bending force. *Stiffener* is a structural element consisting of an elbow or plate that is attached to a structural component to distribute loads, transmit shear, or prevent buckling (SNI 1729:2020). In this study, the plate stiffener used a plate with a thickness of 6 mm and was installed at a distance of every 110 mm by welding. The test results can be seen in Figures 7, Figure 8, and Table 3.

Table 3 is the result of measuring lateral loads on steel frame structures with stiffener plate reinforcement. It can be seen that in the 9th test with a load of 831 kg cracks began to occur on the wall with a length of 120 mm and experienced deformation of 118.7 mm. Figure 8 is a graph of Table 3 data.

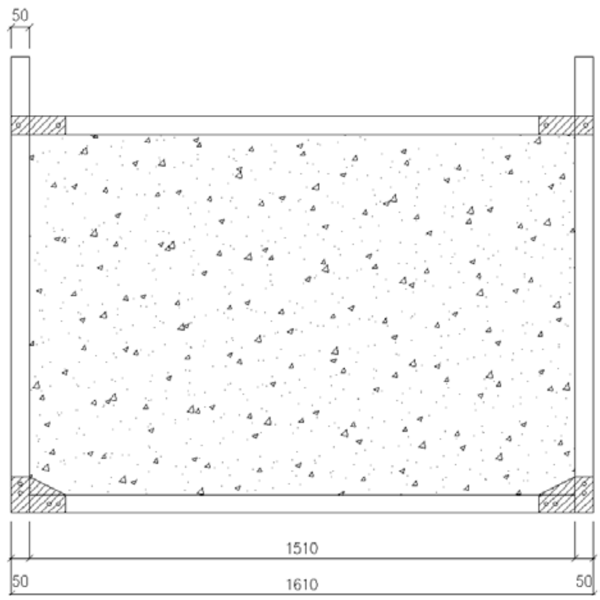


Figure 7. Design to strengthen damaged structural components with plate stiffeners

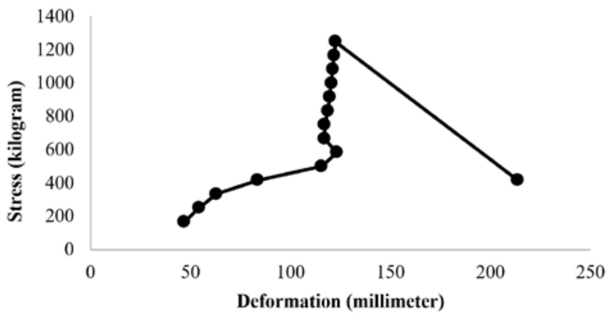


Figure 8. Graph of the Stress and Strain Relationship of Steel Structure Frames (Stiffener Plate)

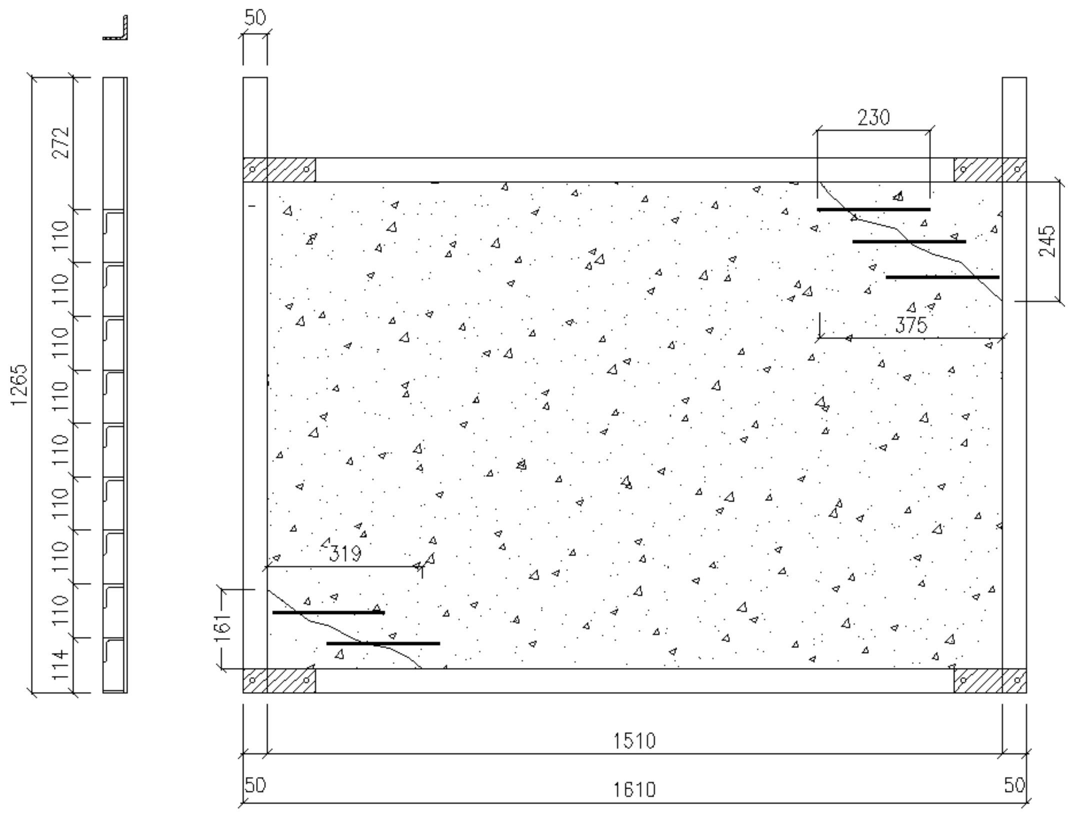
Table 3. Lateral Load Test Results on Steel Structure Frames (Stiffener Plate)

Test	Load (kilogram)	Deformation (millimeter)	Crack (millimeter)
1	166	46,9	
2	249	54,3	
3	332	63	
4	415	83,7	
5	498	115,7	
6	581	123,4	
7	664	116,9	
8	748	117,1	
9	831	118,7	Crack on the top right (120 millimeter)
10	914	119,72	
11	997	120,38	
12	1080	121,2	
13	1163	121,8	
14	1246	122,7	
15	415	213,74	

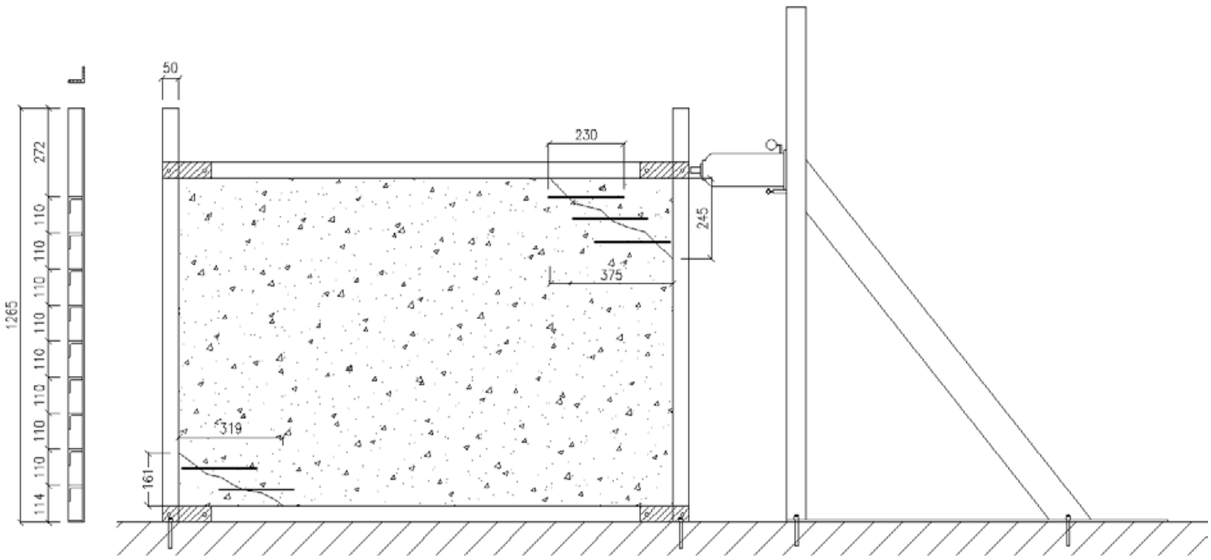
Based on the results of lateral load testing for steel frames with stiffener plate reinforcement, it can be seen that the brick masonry has a strength of 1246 kg with a deflection of 83.5 mm and the wall pair experiences cracks at a pressure of 831 kg. Compared to the steel structure frame before strengthening, the wall cracked at a pressure of 415 kg, so after strengthening with plate stiffeners the strength of the wall increased by 416 kg.

Strengthening Technique with Addition of Reinforcement

The technique for repairing brick masonry that has been partially destroyed is the sewing method. This method is done by perforating two parts in the old wall pair and the new wall pair, then providing reinforcement to tie the two parts together. This method was chosen because the type of wall damage was quite severe and it was likely that if it was repaired it would receive the same load so there were concerns that the section would crack or be destroyed again, so this method was considered the most appropriate to apply to the damage to this pair of walls. The application of repair techniques can be seen in Figure 9, and the results after testing can be seen in Figure 10 and Table 4.



(a)



(b)

Figure 9. Method of strengthening wall cracks using the sewing method (a), its application (b)

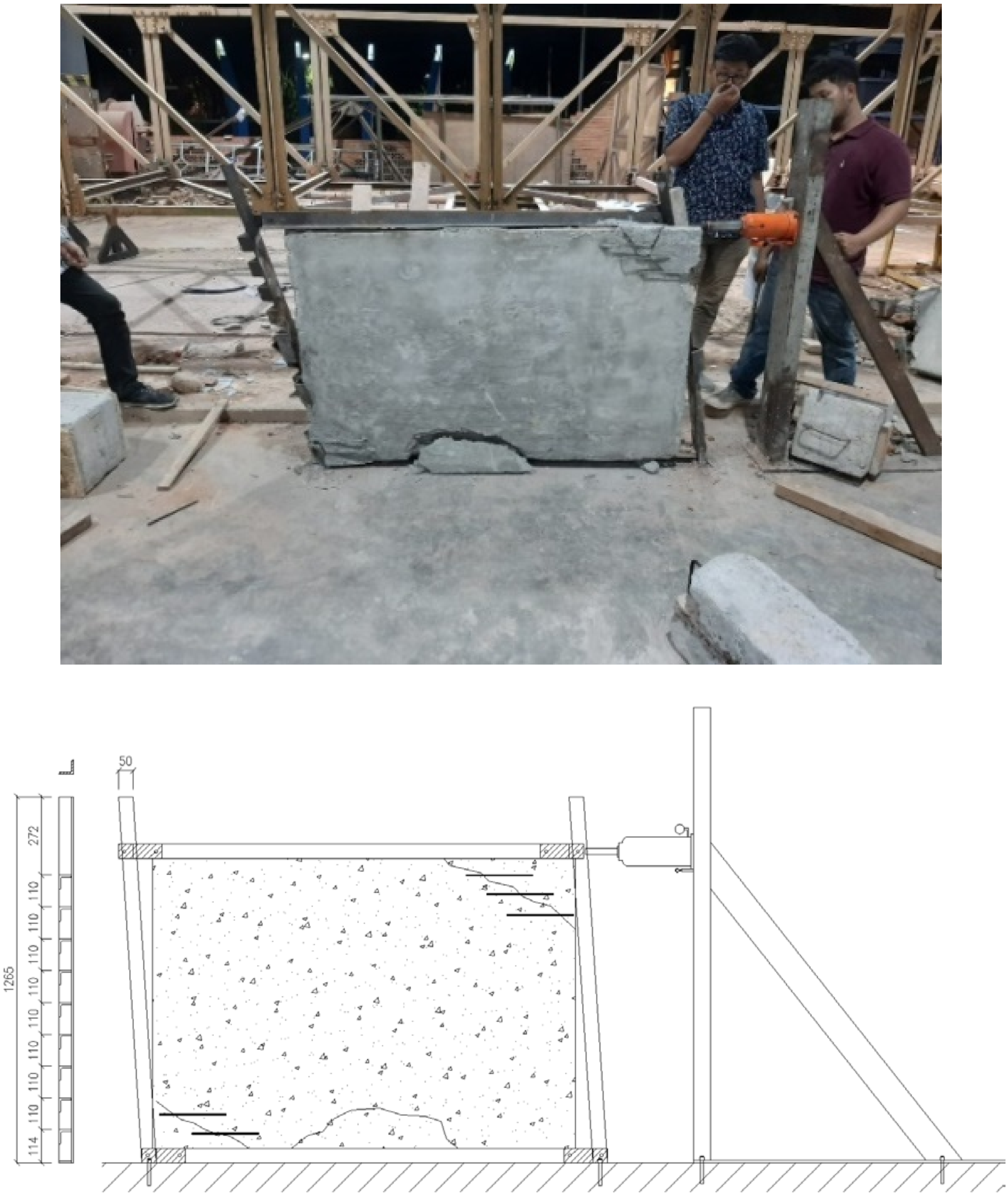


Figure 10. Wall crack repair strength testing

Table 4. Lateral Load Test Results on Steel Structure Frames (Addition of Reinforcement)

Test	Load (kilogram)	Deformation (millimeter)	Crack (millimeter)
1	83	21,64	
2	166	25,68	
3	249	29,66	
4	332	52,6	Line crack
5	415	89,8	
6	498	102,9	Partly fault (not in the repaired area)
7	581	107,46	Fault in the repaired area
8	664	110,1	
9	748	176	

Table 4 is the result of measuring lateral loads on steel frame structures with an addition of reinforcement. It can be seen that in the 7th test with a load of 581 kg, damage began to occur in the repair part and it experienced deformation of 107.46 mm.

Based on the comparison of Table 4, it can be seen that strengthening with the method of adding reinforcement to the wall pair has the greatest compressive strength compared to the wall pair before it is strengthened, namely an increase of 83.06 kg, while the stiffness level experiences a smaller deflection compared to other methods, then for the work is also easy and the cost is cheaper. So it can be concluded that in terms of strength, stiffness, convenience and cost, the most efficient repair technique is to use the method of adding reinforcement to the wall pairs.

In this research, 2 repair methods were carried out to repair wall construction that experienced shear failure. Both methods of repairing the wall calculate the cost incurred for fixing the wall damage. The estimated cost calculation for each method can be seen in Tables 5 and 6. Efficiency analysis based on aspects of strength, stiffness, convenience and cost can be seen in Table 7.

Table 5 is the result of an analysis of the costs required to repair damage to wall construction due to lateral loads using the reinforcement method with stiffener plates.

Table 6 is the result of an analysis of the costs required to repair damage to wall construction due to lateral loads using the reinforcement method with addition of reinforcement.

Table 7 is the result of a comparative analysis between repairing damage to wall construction due to lateral loads using the reinforcement method with stiffener plates and with addition of reinforcement.

Table 5. Budget for Implementation of Strengthening with Plate Stiffener

No	Description	Unit	Quantity	Unit Price (Rp.)	Amount (Rp.)
A	**Material's**				
1	Column Strengthening with plate stiffeners 50x50x5mm	Kilogram	0,883125	22.000,00	19.428,75
2	Dynabold M10	Unit	1	14.000,00	14.000,00
3	Elektroda RD 260, L=350 millimeter	Stem	5	7.000,00	35.000,00
	Amount				**68.428,75**
B	**Instrument**				
1	Hand Cut Grinding Machine	Unit	1	12.000,00	12.000,00
2	Hand Drilling Machine	Unit	1	12.000,00	12.000,00
3	Welding Machine	Unit	1	150.000,00	150.000,00
4	Meter Tool	Unit	1	4.000,00	4.000,00
5	Welding Glasses	Unit	1	2.000,00	2.000,00
	Amount				**180.000,00**
C	**Employee**				
1	Employee	Daily Person	3	145.000,00	435.000,00
	Amount				**435.000,00**
D	**Sum A + B + C**				**683.428,75**
E	***Overhead dan Profit (0 %)***				**0,00**
F	**Unit Price of Work (D + E)**				**683.428,75**

Table 6. Budget for Implementation of Strengthening with Additional Reinforcement

No	Description	Unit	Quantity	Unit Price (Rp.)	Amount (Rp.)
A	**Materia's**				
1	Cement	Kilogram	5	7000	35.000,00
2	Sand	Kilogram	10	3000	30.000,00
3	Red Brick	Unit	8	1500	12.000,00
4	Dynabold M10	Unit	1	15.000,00	15.000,00
5	Plain Reinforcing Steel d 8 millimeter	meters	0,8	12.500,00	10.000,00
	Amount				**102.000,00**
B	**Instrument**				
1	Hand Cut Grinding Machine	Unit	1	12.000,00	12.000,00
2	Hand Drilling Machine	Unit	1	12.000,00	12.000,00
3	Meter Tool	Unit	1	4.000,00	4.000,00
	Amount				**28.000,00**
C	**Employee**				
1	Employee	Daily Person	1,125	145.000,00	163.125,00
	Amount				**163.125,00**
D	**Sum A + B + C**				**293.125,00**
E	***Overhead dan Profit (0 %)***				**0,00**
F	**Unit Price of Work (D + E)**				**293.125,00**

Table 7. Comparison of results from wall construction repair methods

Metode	Strength	Stiffness	Workability	Amount
Strengthening Technique with Plate Stiffener	831 kilogram	At a compression of 581 kilogram, it experiences a deformation of 123.4 mm	Easy	Rp. 683.428,75
Strengthening Technique with Addition of Reinforcement	581 kilogram	At a compression of 581 kilogram, it experiences a deformation of 107,46 millimeter	Easy	Rp. 293.125,00

4. Conclusions

Based on the test results at a load of 498 kg for a steel frame structure without brick masonry, there was a deflection of 75mm, while for a frame structure with masonry there was a deflection of 27mm steel. However, brick walls can also accelerate the structure's collapse if the wall pairs are stronger than the steel structure, because brick walls push steel columns which should receive tensile forces due to lateral forces, but instead receive bending forces when pushed by bricks, this is directly proportional. With test results on a steel structure frame without brick masonry, it has a strength of 1329 kg, while a steel structure frame with brick masonry has a smaller strength, namely 498 kg.

Based on the test results and analysis of the efficiency of repair techniques, it can be seen that the most efficient technique for repairing structural cracks due to shear collapse is using the method of adding reinforcement to the walls, this method is able to withstand a lateral load of 581 kg and requires an implementation cost of Rp. 293,125.00.

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