

RESEARCH ARTICLE

Repair of buckled steel braces via buckling zone relocation method

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Abstract

In this study a new repair method, called buckling zone relocation, for buckled steel braces is presented. In this method, buckled zone of the steel brace is wrapped with steel plates to relocate the buckling zone toward the undamaged locations of the brace. Thus, the brace can be reach buckling load again. The effectiveness of the proposed method was experimentally investigated. To do this, 2 tubular brace specimens, each have 2000 mm length and 70×70×3 mm cross section, were subjected to quasi-static cyclic loadings. First specimen were loaded until global buckling and then unloaded to repair with the proposed method. The length of the buckling zone to be repaired with steel plates was determined with finite element analysis. When the repair process completed, the specimen reloaded until collapse. The second specimen was loaded until collapse to be used as reference member. As a result, it was determined that the buckled steel brace tested in this study could been effectively repaired via buckling zone relocation method without any significant decrease in its performance.

1. Introduction

Steel braces are commonly used lateral force resisting systems in the structures due to their ease of fabrication and high lateral stiffness. The expected behavior from these systems is to limit the lateral translation of the structure, but also to dissipate energy through yielding in tension and buckling in compression [1]. Steel braces are usually buckled at 0.3-0.5% drift ratio levels and plastic hinges occur before the other structural elements [2,3]. However, buckled steel braces lose their load carrying capacity to a large extent under the effect of compression. This situation is very important for repairable structures where controlled damage is provided in earthquakes.

The importance of repair and strengthening which was always up-to-date for reinforced concrete and masonry structures has been better understood, especially after the 1994 Northridge earthquake, for steel structures and various regulations have been prepared [4,5]. The studies carried out to date have generally focused on repairing and strengthening of damaged columns, beams and connection [6-10]. As for steel braces, researchers have generally been studied on strengthening issues [11,12].

In this study, a simple and effective repair method is proposed for buckled steel braces. Within the scope of the study, the experimental behavior of a buckled steel brace repaired via the buckling zone relocation method was examined and the results were discussed.

2. Buckling zone relocation method

In buckled steel braces, the damage is concentrated in the middle of the brace and plastic hinge occur in this region. As moving away from the plastic hinge region, plastic deformations gradually decrease and leave their place to elastic deformations. With the buckling zone relocation method, the region having plastic deformation is strengthened by wrapping steel plates and the buckled zone is bypassed by transferring the load with the wrapping plates to undamaged zones. Thus, in a possible earthquake, the buckling will be shifted to the elastic regions of the brace and the buckling load will be reached again. The length of the plastic region should be determined by numerical studies or experimental measurements. The suggested repair method is shown schematically in Fig. 1. First of all, the buckled zone should be wrapped with red colored plates. These plates are welded from all sides to the steel brace, thus bypassing the buckled zone. In this case, if reloading is carried out, the buckling will occur in one of the free ends close to the red plate. In order to remove the buckling from the welded ends of the red plate, the green colored additional wrapping plates should be joined by welding the ends of the red plate. The other ends of the green wrapping plates should be free.

3. Experimental studies

3.1. Specimens and Test Setup

Two test specimens named C1 and C2 were fabricated at the structural laboratory of Karadeniz Technical University to investigate effectiveness of suggested repair method under displacement controlled cyclic loading. The C1 and C2 specimens consist of a square HSS $70 \times 70 \times 3$ mm load bearing member with pinned connection members at each end. The total length of the entire assembly, from pin to pin, and the load bearing member are 2000 mm and 1740 mm, respectively (Fig. 2).

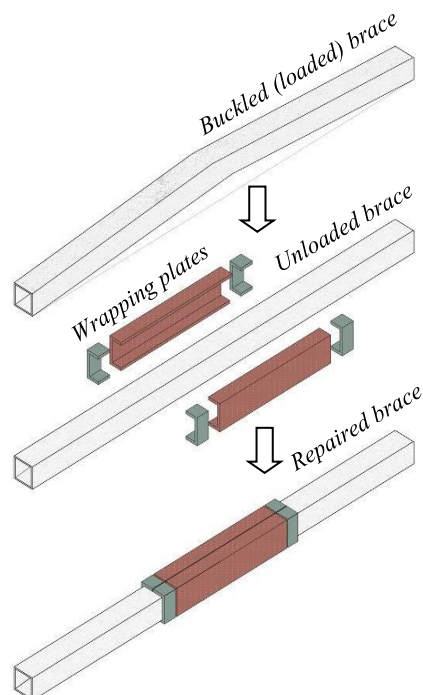


Fig. 1. Schematic view of the suggested repair method

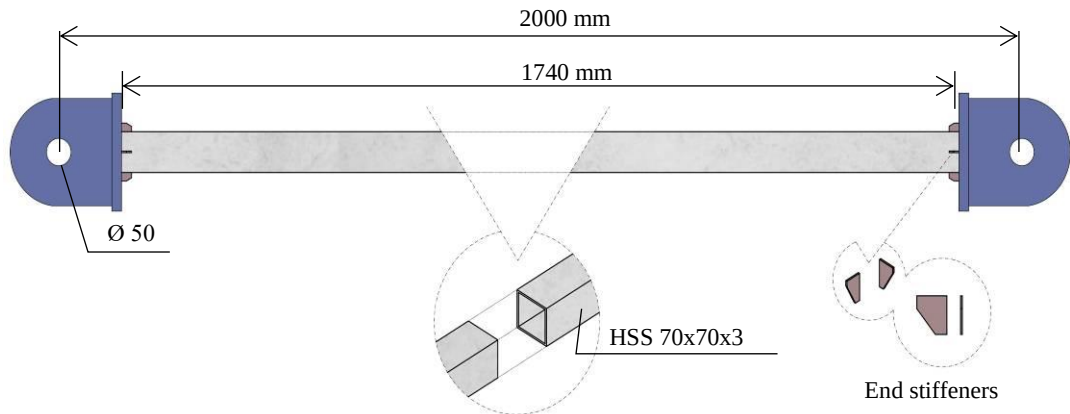


Fig. 2. Dimensions of the specimens (mm)

C1 specimen is planned to be repaired after being buckled as a result of cyclic loading. That's why, in the first stage, the entire loading protocol will not be applied to C1 specimen, instead, it will be tested until it buckles. After the C1 specimen is buckled, it will be unloaded to its original position and repair will be carried out. Then, as a second stage, the entire loading protocol will be applied to repaired specimen named C1-R to examine the overall performance under cyclic loading. The C2 specimen is the reference sample and will be tested under the cyclic loading applying the entire loading protocol. The results will be compared with the repaired test element.

The experimental setup consists of a stiff loading column and beam with pinned end joints as shown in Fig. 3. Cyclic loadings were carried out with a displacement-controlled hydraulic actuator, and the loading protocol used in the experiments is given in Table 1. During the experiments, load measurements were made with a load cell having a capacity of 500 kN placed at the end of the hydraulic actuator. The horizontal displacement of the loading column was measured with a displacement. The locations of the loadcell and displacement transducer (LVDT) were shown in Fig. 3. The actuator horizontal displacement was measured from loading point. All measurements were recorded with a Coda AI8b data acquisition system.

4. Results and discussions

4.1. First stage experiment results

In the first stage, the C1 specimen was tested under cyclic load until buckling. C1 specimen showed elastic behavior during the first displacement step. In the second displacement step, the specimen loaded until buckling and the maximum compression load of 165.57 kN was reached at a horizontal displacement of 4.48 mm. In the first cycle of the third displacement step, buckling occurred at a displacement of 4.58 mm and a load level of 158.97 kN (Fig. 4). Immediately after the buckling, there was a sudden decrease in the load. After this stage, the hydraulic actuator unloaded to the zero position and the repair stage was started.

4.2. Repair via buckling zone relocation method

The region where plastic deformations occurred in the C1 specimen to be repaired via buckling zone relocation method was determined with three-dimensional nonlinear finite element analysis. C1 specimen were modeled in the ANSYS software [13] using SOLID185, 8-node tetrahedral element, which has stress stiffening, large deflection and large strain capabilities, as well as three degrees of freedom at each node: transition in the nodal x , y and z directions.

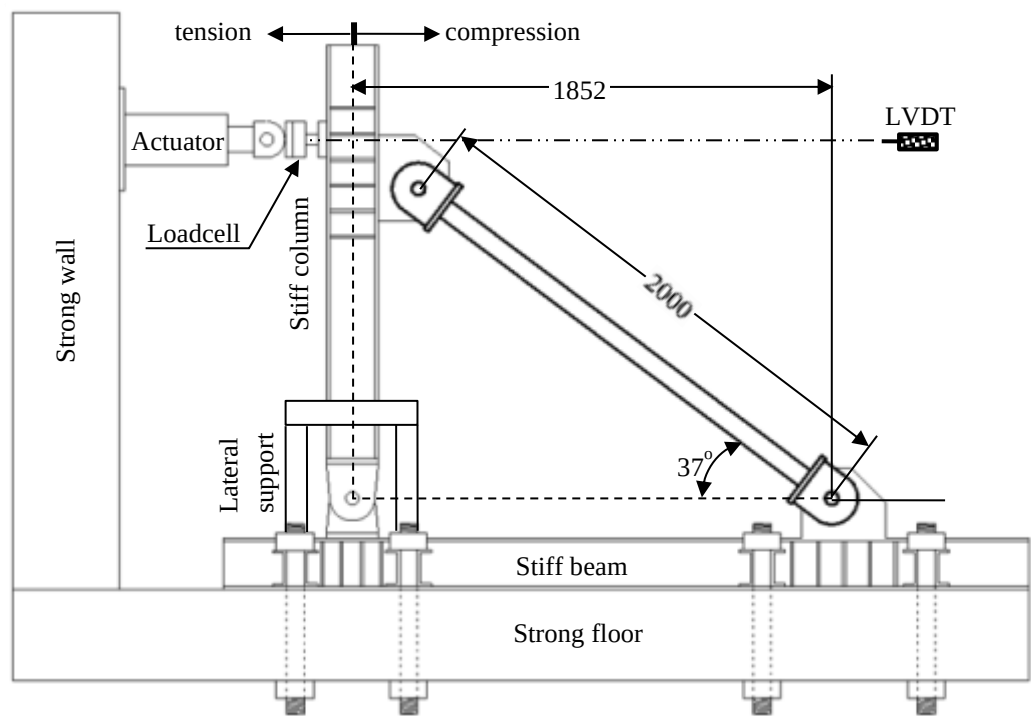


Fig. 3. Test setup (mm)

Table 1. Loading protocol

Step	Cycle	Number and amplitudes of cycles	Drift ratio
1	1,2	2@2 mm	-
2	3,4	2@5 mm	% 0.36
3	5,6	2@13.95 mm	% 1.00
4	7,8	2@27.90 mm	%2.00

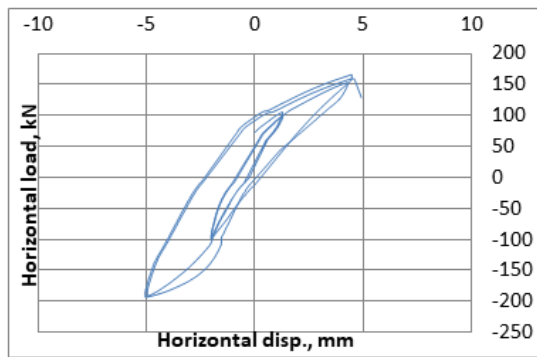


Fig. 4. The cyclic behavior of the C1 specimen until buckling

As a result of the analyzes, the strain distribution values on the upper and lower faces along the clear length of the C1 element (1740 mm) was obtained and it was determined that plastic deformations occurred along a length of approximately 600 mm in the middle region (Fig. 5). A hollow structural section with a length of

600 mm and a cross section of $80 \times 80 \times 4$ mm was cut in half to be used as a wrapping plate (Fig. 6). The region of plastic deformation was repaired by wrapping these plates and C1_R element was obtained. In the repair process, first of all, 600 mm long wrapping plates (red) were placed on the test specimen to cover the damaged area. Then they were welded to the C1 specimen at their free ends. In order to remove the local buckling from the welded ends of the wrapping plates in the cyclic loading to be applied, additional 50 mm long wrapping plates (green) were welded to the repaired area from both ends. The other ends of the additional wrapping plates left free (Fig. 7).

4.3. Second stage experiment results

In the second stage, the repaired test specimen C1_R and C2 were tested under full loading protocol. The test results are summarized in Table 2.

The C1_R specimen has reached its buckling limit load in the second displacement step. In the first cycle of the third displacement step, buckling happened at a horizontal displacement of 4.63 mm and a horizontal load of 162.85 kN. Immediately after the buckling, there was a sudden drop in load. At the same displacement step local buckling occurred in the free region of the brace, outside the repaired region, at the horizontal displacement level of approximately 10.11 mm. In the following cycles, the damage was concentrated in the local buckling region and the load carrying capacity of the C1_R specimen decreased to 44.91 kN. At the same displacement step, horizontal load reached a maximum value of -218.32 kN at a horizontal displacement of -13.17 mm in tension. The corner cracks occurring in the local buckling region of the C1_R specimen gradually increased in the first cycle of the fourth displacement step and the specimen collapsed from this region at -24.43 mm horizontal displacement in tension (Fig. 8).

Specimen C2 has reached its buckling limit in the first cycle of the second displacement step. In the first cycle of the third displacement step, global buckling occurred. At the time of buckling the horizontal displacement and load was 4.52 mm and 163.85 kN, respectively. Local buckling occurred in the middle region of the brace at a horizontal displacement of about 10.27 mm in the same cycle. In the following cycles, the damage is concentrated in the local buckling region. While the load carrying capacity of the C2 specimen decreased to 16.02 kN in compression at a 2% relative storey drift ratio, the test specimen collapsed at a horizontal displacement of -21.28 mm in tension (Fig. 9).

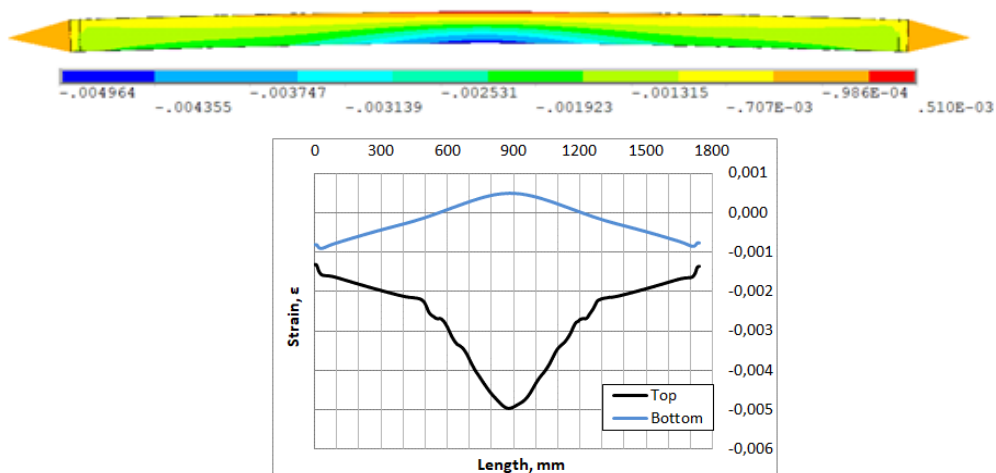


Fig. 5. Strain distribution along the C1 specimen



Fig. 6. Wrapping plates

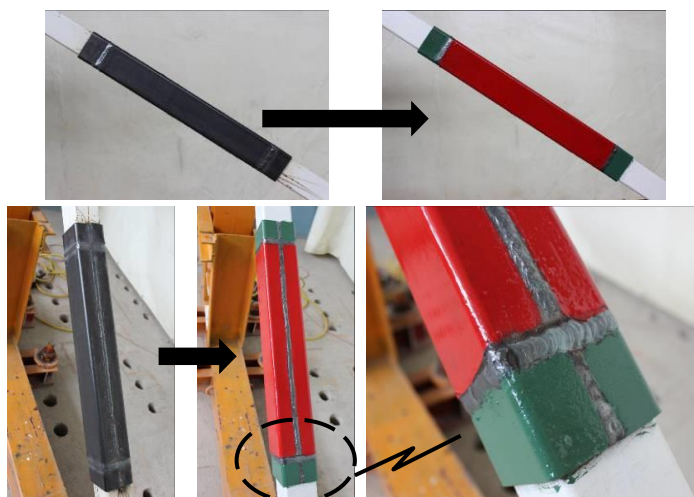


Fig. 7. C1_R specimen repaired by the buckling zone relocation method

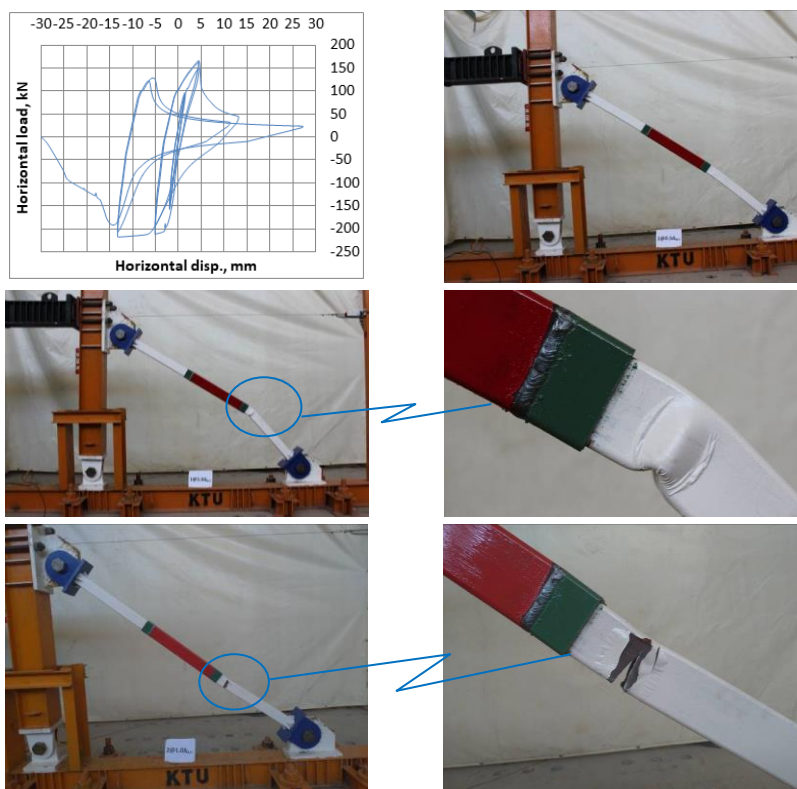


Fig. 8. Cyclic behavior of C1_R

Table 2. Results summary

Specimen	Buckling load (Compression (+))			Yield load (Tension (-))		
	P_c (kN)	Δ_c (mm)	K_c (kN/mm)	P_y (kN)	δ_y (mm)	K_y (kN/mm)
C1	158.97	4.58	34.71	-193.65	-5.01	38.65
C2	163.85	4.52	36.25	-192.90	-4.60	41.93
C1_R	162.85	4.63	35.17	-211.59	-5.12	41.32

Specimen	Maximum load			
	Compression (+)		Tension (-)	
	$P_{c,max}$ (kN)	$\delta_{c,max}$ (mm)	$P_{t,max}$ (kN)	$\delta_{t,max}$ (mm)
C1	165.57	4.48	-193.65	-5.01
C2	165.10	4.40	-211.50	-13.50
C1_R	166.46	4.44	-218.32	-13.17

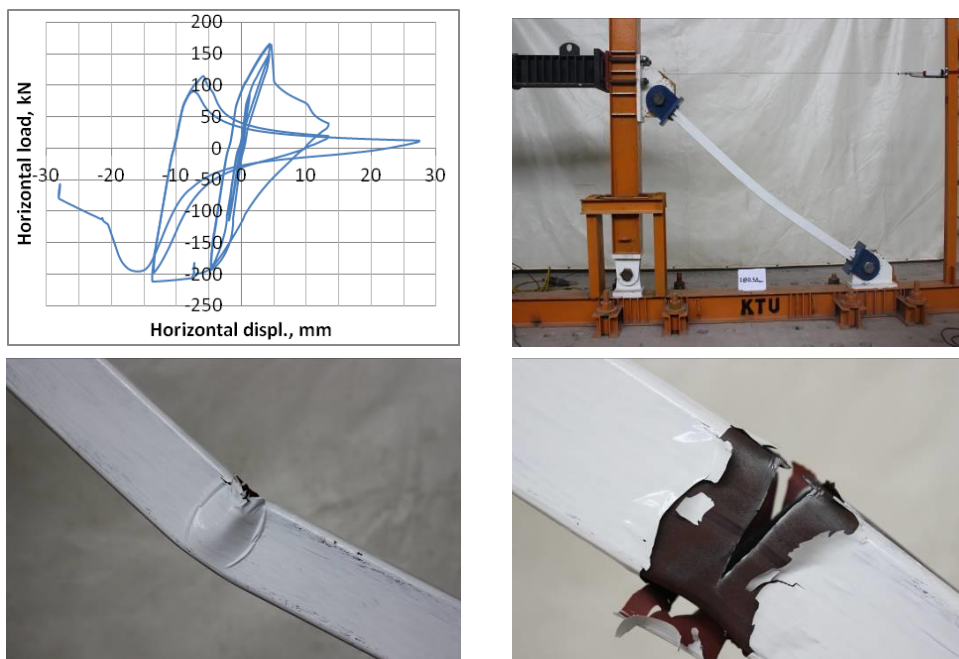


Fig. 9. Cyclic behavior of C2

5. Conclusions

In this study, experimental studies on the repair of buckled steel braces with the buckling zone relocation method are presented. Within the scope of the study, a steel brace loaded until global buckling and then repaired via buckling zone relocation method. When the experimental results were examined, it was seen that approximately the same buckling load could be reached again in the test specimen repaired by the buckling zone relocation method. As aimed before the repair, red colored plate provided an additional rigidity to the buckled zone, and re-moved the re-buckling to the un-wrapped regions of the brace. Furthermore, it

was observed that there was no decrease in the fracture life of the repaired test specimen. It is thought that the green plates prevent the reduction of fracture life by removing the buckling from the welded area. According to these results, it can be said that the buckling zone relocation method is an effective and simple repair method for buckled steel braces having square cross sections.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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