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Experimental evaluation of certain repair techniques for cracked structural steel components

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This paper investigates the appropriateness and effectiveness of certain repair techniques for cracked structural steel components. Generally, there exist two options for dealing with cracked steel components; either replacement or repair. This paper focuses on the cases where replacing the cracked component(s) is not feasible at the time of crack(s) discovery, however, replacement will take place in the future. Thus, the repaired component will serve in the structure for a specified time depending on the inspection. Also, the level of inspection after repair is assumed to be adequate. The main goal of the investigation is to address the problem of retaining the original load carrying capacity of the component in both yield and ultimate loads with adequate ductility. Seven different repair techniques with two main repair technique categories have been considered; direct welding of the crack faces using Gas Metal Arc Welding (GMAW) or splicing the wake of the crack either by welding or bolting. Two specimens of each technique have been tested. For the first category, different blunting hole diameter (5, 10 and 15 mm), and different preparation of crack faces prior to welding (grooved vs. non-grooved) have been considered. Results have shown that most of the repair techniques have succeeded in retaining the initial yield load of the component, however, only three techniques have shown similar ultimate load to the virgin specimen. The most successful technique using direct welding of the crack faces is to groove the crack faces and to blunt the crack tip with a hole diameter of 10 mm or less. Larger hole diameter would increase the yield load capacity with a considerable reduction in both ultimate load and ductility. On the other hand, the direct application of welding to the crack faces without either blunting or grooving the crack faces has shown the worst results. Splicing the crack wake through welded splices using GMAW is efficient in retaining both the load carrying capacity and the ductility of the virgin specimen provided that the weld thickness should be designed such that the failure occurs outside the splice zone.

يتناول هذا البحث مدى ملاءمة و فاعلية بعض تقنيات ترميم العناصر الإنشائية المصنوعة من الصلب و التى تعانى من وجود شروخ بها و ذلك من خلال برنامج بحث عملى. و يركز البحث على الحالات التى يصعب معها و قت إكتشاف الشروخ إستبدال العنصر المعطوب مع إمكانية تغييره فى المستقبل و من ثم فإن العنصر المرمم سوف يبقى فى الخدمة لفترة محددة مع إفتراض وجود صيانة و كشف دورى بعد الترميم. الهدف الأساسى للبحث هو تقييم هذه التقنيات من حيث إستعادة قدرة العضو الإنشائى على تحمل حملى الخضوع و الأقصى للعينات البكر بدون شروخ و بممطولية مقبولة. تم إستخدام سبعة تقنيات مختلفة للترميم يمكن تقسيمها إلى مجموعتين: الأولى تختص بلحام أوجه الشروخ مباشرة عن طريق لحام القوس ذو الغاز المحيط و الثانية تختص بعمل وصلة خارجية لوصل أوجه الشرخ إما عن طريق اللحام أو المسامير. تمت دراسة أهمية تبليد أطراف الشروخ وكذلك تجهيز أوجه الشروخ عن طريق عمل أخاديد للحام و قد تم إستخدام أقطار لدوائر تبليد الشروخ قدرها ٥ و ١٠ و ١٥ مم و تم عمل عدة توافقيات لتغطية معظم الإحتمالات. أظهرت النتائج أن معظم التقنيات نجحت فى تحقيق حمل خضوع مماثل لذلك الخاص بالعينة البكر على أن ثلاثة طرق فقط هى التى تمكنت من تحقيق حمل أقصى مقارب للعينة البكر. كما أظهرت النتائج أن تبليد الشروخ بقطر ١٠ مم أو أقل مع عمل أخاديد لأوجه الشرخ لتحسين اللحام هو الأفضل بالنسبة للمجموعة الأولى من ناحية الأحمال و الممطولية مع مراعاة أن اللحام المباشر للأوجة بدون أى إعداد قد أظهر أسوأ النتائج على الإطلاق. من ناحية أخرى فأن عمل وصلة تراكبية على منطقة الشرخ بواسطة اللحام هى الأفضل على الإطلاق بشرط أن يصمم اللحام بحيث يكون الكسر خارج حدود الوصلة.

Keywords: Crack, Steel, Blunting, Welding, Splice

1. Introduction and background

Ductile behavior of steel structures and components is the main theme in most building code provisions, particularly under laterally applied loads (e.g. seismic loads). Accomplishing this behavior is usually inherited in modern code provisions through the proper choice of building materials, structural system, and detailing of joints. Generally speaking, a steel structure is considered to behave in a ductile fashion if it is capable of withstanding large inelastic deformations without significant strength degradation or loss of stability.

Unfortunately, this paradigm has been challenged by recent surveys of many steel structures, which were designed according to the ductility-criterion code provisions. Cracks have been detected in these structures due to fatigue loading, accidental lateral loading, or aggressive environment. For instance, it has been reported by FEMA-531 [1] that a number of welded steel moment-frame buildings were found to have experienced brittle fractures of beam-to-column connections after the Northridge earthquake of 1994. Also, Fisher and Mertz [2] have collected several cases of steel bridge structures where several cracks have been detected due to load related causes.

Cracks represent a discontinuity in the structure or a component decreasing its load carrying capacity, accelerating its degradation, and reducing its useful life. As a result of this strength reduction, cracked members and connections operate at a lower safety factor than that intended in design. Consequently, a decision should be taken regarding raising the factor of safety again to an appropriate level. This can be achieved either by adjusting the load conditions, replacing the cracked component, or conducting a repair job. Usually, the first option is not feasible as it restricts the use of the structure significantly.

Furthermore, due to the sharp tips of the cracks, the stress and strain fields around these tips aggravate the potential of crack advance, particularly under fatigue loading or corrosive environment. It is well-established [3] that the existence of cracks in themselves does not mean failure, however, they represent a high potential for crack advance and propagation leading to failure. This type of failure is always associated with catastrophic collapse reducing the ductility of the structure significantly.

Periodic inspection of steel structures for cracks, particularly those exposed to adverse conditions, represents the cornerstone in maintaining their useful life. Methods of the periodic and detailed inspection for steel structures for cracks are available elsewhere [4}. If a crack(s) is located in a certain structure or component, the engineer is faced with two main options; either replacement or repair of the cracked component(s). The choice of either option is highly dependent on the following issues which can be summarized as [5]:

a. The basic cause(s) of the cracking, whether load or environmental related, should be determined. This cause(s) should be eliminated, or at least minimized; otherwise, it is most likely that the cracking will reoccur.

b. Level of the expected useful life of the structure, e.g., if the structure is expected to be in service for a short time, a less expensive repair would suffice and vice versa.

c. Level of inspection frequency, if the structure is to be inspected in relatively longer periods, a more thorough repair, or even replacement should be considered.

d. Site constraints, as the repair jobs must be in site, thus, the accessibility of the cracked component, the appropriateness of conducting welding processes, the ease of shoring the structure if needed, and similar site constraints might affect the choice of the repair strategy and quality considerably.

2. Research focus

The main theme of this research is to evaluate the appropriateness of different repair techniques for cracked steel components. The research is concerned particularly with the cases where replacing the cracked component(s) is not feasible at the time of crack(s) discovery, however, replacement will take place in the future. Thus, the repaired component will serve in the structure for a specified time depending on the inspection. Also, the level of inspection after repair is assumed to be adequate.

3. Repair concept

The main goal of this research is to evaluate the effectiveness of the proposed repair techniques to retain the full or partial initial load carrying capacity of the component with adequate ductility. This procedure conducting in achieving this goal is based on certain concepts.

As well established [3], there are two issues associated with crack existence; the first is the sharpness of the crack tip which is linked directly to the very high stress and strain field around that tip. This, in turn, gives high potential for cleavage rather than dislocation emission [6]. The cleavage of a crack leads to catastrophic fracture and brittle behavior (the second issue; e.g. ductility). In order to retain the initial load carrying capacity, one has to make use of the almost stress free zone awake of the crack tip. This can be achieved through reconnecting the crack faces either by direct welding, or splicing with plates. However, reducing the intensity of the stress field at the crack tip is also of vital importance to reduce any future crack advance due to fatigue loading or aggressive environment. This can be achieved successfully through blunting the crack tip with hole-drilling. The issue of blunting the crack tip has been investigated theoretically, experimentally, and numerically by the author [7], and more details about this concept is available elsewhere [8-10].

4. Repair procedures

In conducting the repair concept as explained before, several procedures has been implemented in order to achieve the goals of the research. These procedures include; blunting the crack tip, preparation of the crack faces for welding, and welding. In the following sections, details for these procedures will be discussed.

4.1. Blunting the crack tip

As per the Egyptian Code of practice (article 14.3.1.9) [11], the crack propagation may be stopped through blunting the crack tip by drilling a hole of 15 mm diameter at the tip. The issue of adequate hole size for easing the stress field has been discussed in detail elsewhere [7]. This investigation has revealed that a 5 mm hole would suffice to blunt the crack tip and initiate a dislocation emission leading to ductile behavior. For the sake of comparison, three sizes of hole diameters have been considered in this study namely; 5, 10, and 15 mm, respectively, to cover the range between the research and code provision. Drilling the holes has been conducted using a general purpose rotary drill.

4.2. Preparation the crack faces' edges

As one of the repairing techniques proposed in this study is to apply a double V butt weld, thus, some of the specimens have been prepared by grooving the crack faces to the double V using a general purpose rotary cutter. The root opening after grooving the crack faces was in the order of 2-3 mm.

4.3. Welding

Generally, welding is not a recommended practice in most codes for crack repair as it might represent a high potential for reoccurrence of cracks in the same location. There is an exception of using welding in crack repair in the Egyptian Code [11] in cases where riveting or bolting is not possible. Welding zones are usually susceptible to cracking due to improper welding, residual stresses, or incrassated brittleness due to heating and increasing the yield stress (usually the fracture toughness is inversely proportioned to yield stress). In order to minimize such effects, the Gas Shielded metal Arc Welding (GSAW) has been used. The type used in this study is the one uses carbon dioxide (CO2) as an active gas. It has been found that this type of welding produces less distortion without any bracing of the specimens due to lower heat and all the test specimens were touched even after 5 minutes of welding. Upon applying the weld deposits, cleanliness has been granted through removing of rust, dirt, grease, oil and other contaminants from the surfaces to be welded. After the application of weld, for some specimens with grooving, the access weld was grind to be leveled with the original specimen surface.

5. Experimental program

As mentioned before, repair of cracked steel components is not straight forward and several factors may enter into the picture changing the methodology of repair. This issue has been reflected directly into the experimental program where different configurations have been evaluated. Fig. 1 shows the layout of the experimental program where seven configurations for the repair technique has been conducted namely, S1 to S7, respectively. The configurations and details of all specimens are shown in fig. 2 through fig. 5, where all specimens are 100x600 mm with 10 mm thickness. The repair techniques can be classified into two main categories; the direct deposit of welding onto the crack faces, or the splicing of the crack wake. In order to cover the different possibilities in the first category, the specimen S5, is directly welded without any preparation for either the crack faces or blunting the crack tip, while the crack faces of S4 is grooved, but without blunting the crack tip. On the other hand, a group of three specimens namely, S1, S2, and S3, have been well-prepared by both grooving the crack faces for butt welding, and their tips have been blunted using a 5, 10, and 15 mm holes, respectively. For all double V butt weld specimens, the access weld was grinded and leveled with the original plate thickness. With respect to the second category, all test specimens have been blunted using a 5 mm hole, and spliced with two 50x140 mm plates of 5 mm thickness. The splice plates are either welded with a 5 mm thickness fillet weld along the top and bottom edges for S6, or bolted with two M8 high strength bolts at either side of the crack for S7. Two specimens of each has been tested under uniaxial tension in a stiff universal machine of 1000 kN capacity as shown in fig. 6. Both the yielding and ultimate loads for each specimen were recorded and the mode of failure for each specimen has been analyzed.

The previous combinations cover most of the cases that can be adopted in repair in the context of the research purpose.

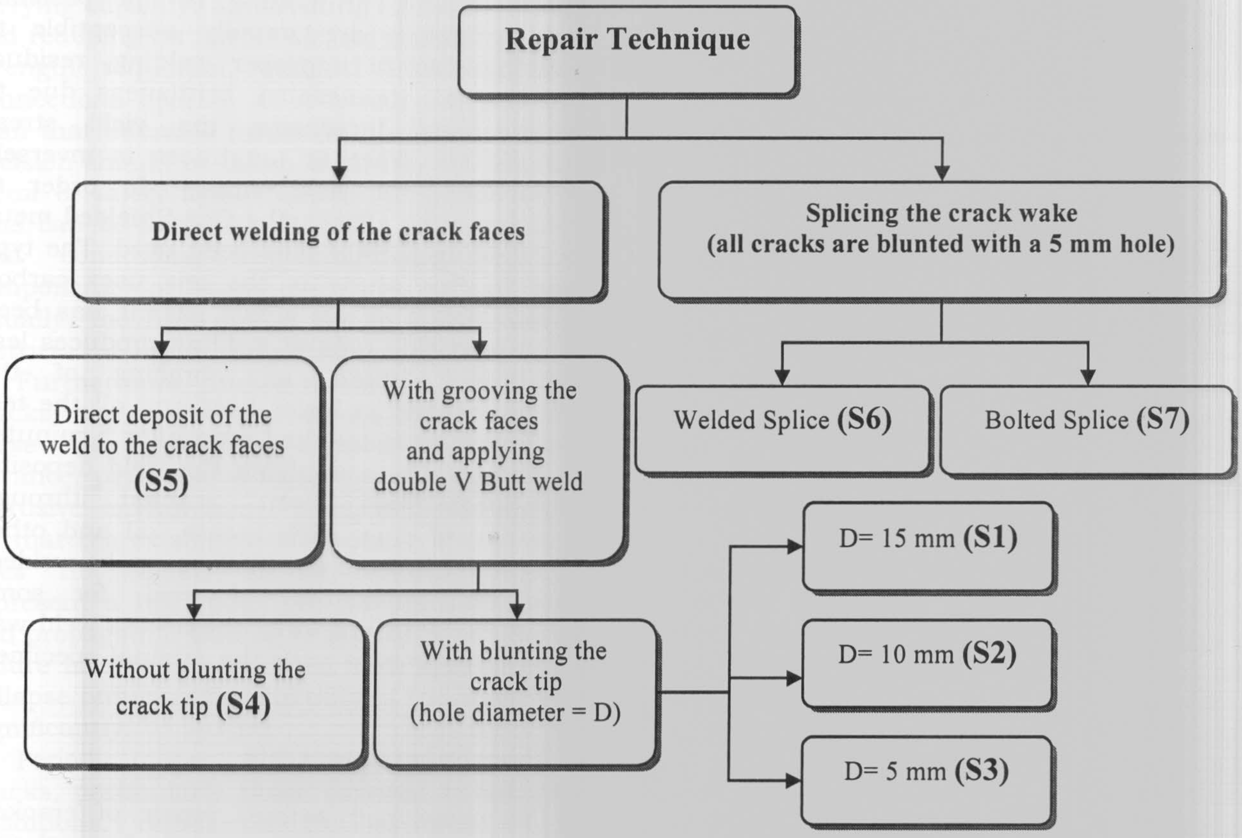
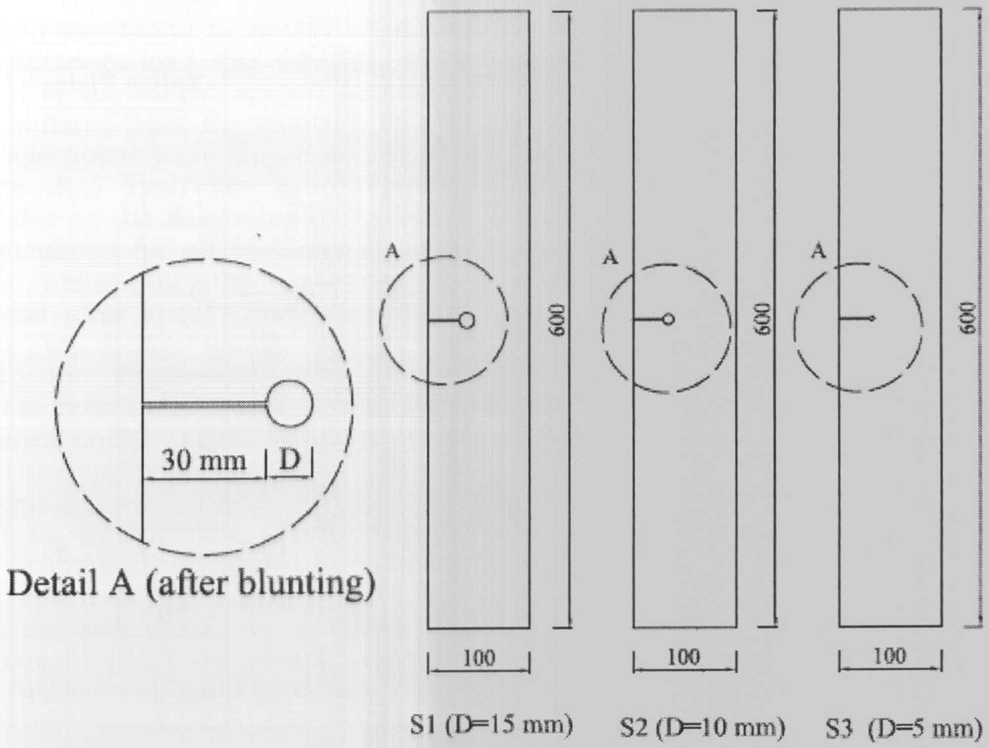
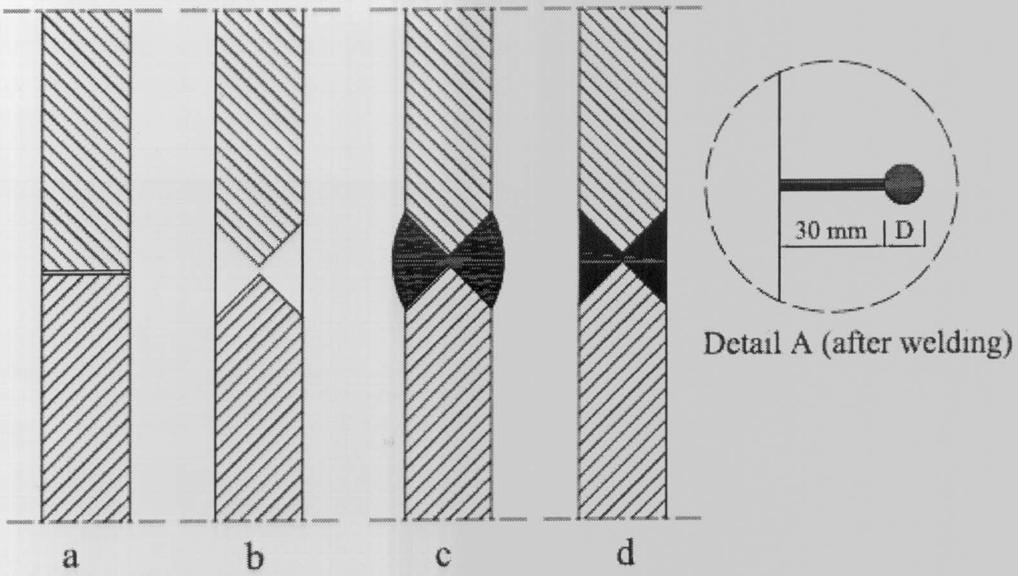


Fig. 1. Layout of the experimental program.



i) Specimen configurations and details of blunting for specimens S1 to S3



Ii) Specimen preparation for double V butt weld; a) original crack, b) grooving the crack faces, c) depositing the weld, and d) grinding the weld.

Fig. 2. Configuration and steps of repair for specimens S1, S2, and S3.

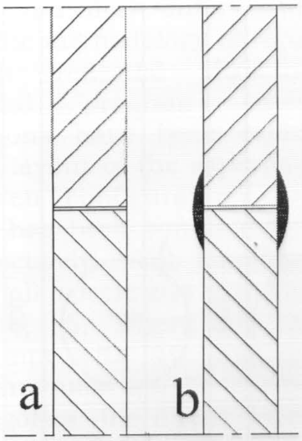


Fig. 3. Repair steps for specimen S5; a) original crack without blunting nor grooving, and b) direct depositing of weld without grinding.

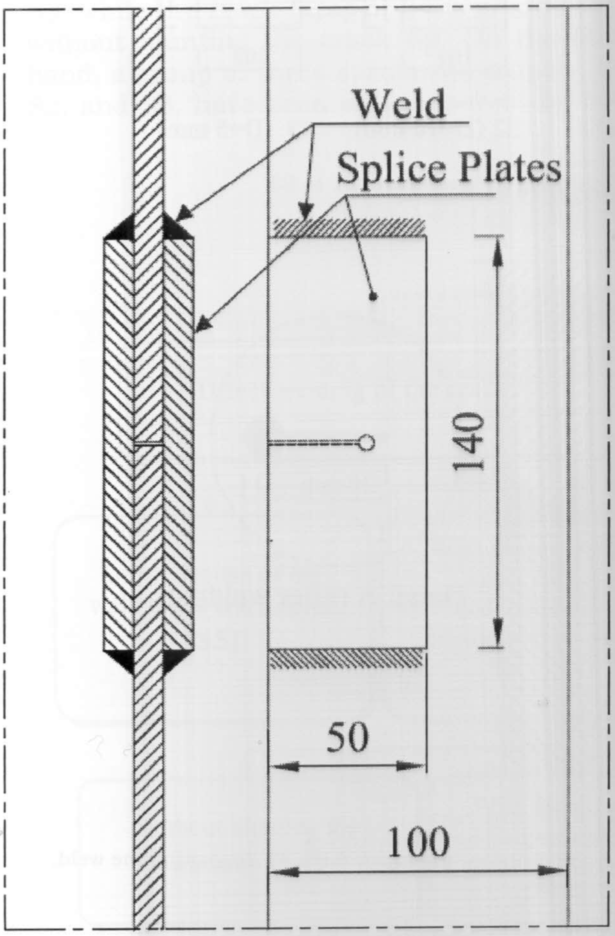


Fig. 4. Details for specimen S6, the crack tip is blunted with a 5 mm hole followed by splicing the crack wake with welded plates.

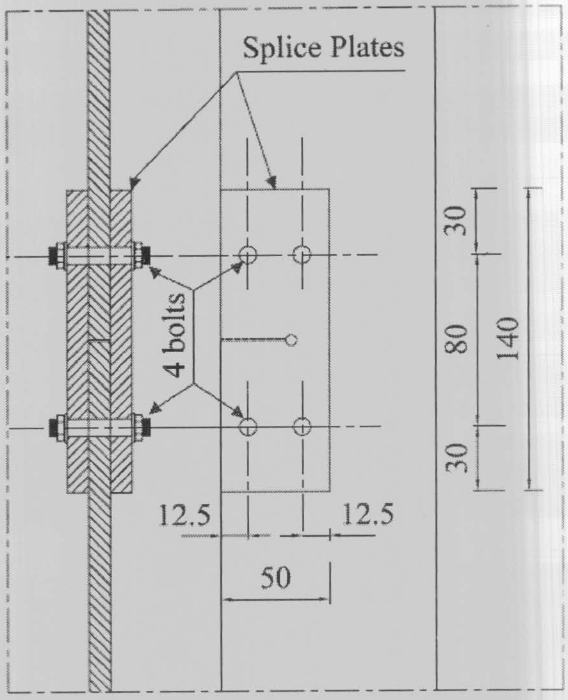


Fig. 5. Details for specimen S7, the crack tip is blunted with a 5 mm hole followed by splicing the crack wake with bolted plates.

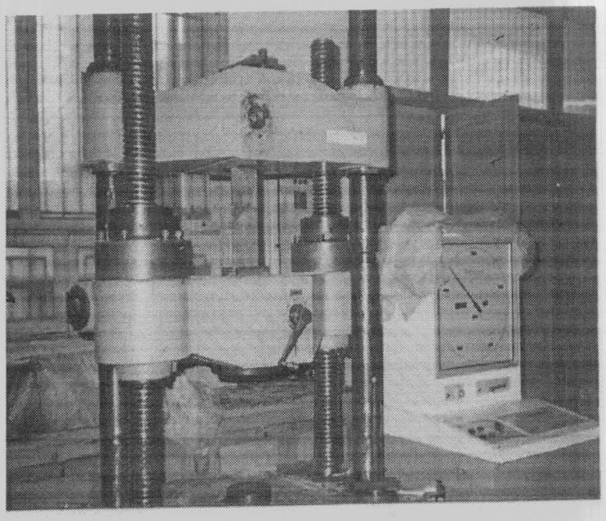


Fig. 6. Test set-up (specimen S3).

6. Results and discussion

Test results for all specimens are given in table 1 together with the average of the two specimens. For the sake of comparison, the average yield load for the virgin specimens (without notch) was found to be 294 kN while the average ultimate load was 409 kN. With the exception of the bolted spliced specimen (S7), which suffered from a premature failure of bolts, all specimens have shown a yield (P_y) and ultimate (P_{ult}) load. The ratio (P_{ult}/P_y), referred to later as the hardening index (*H.I.*), has been calculated for all specimens and it reflects the ability of the specimen to withstand load after yield. This ratio ranges from 1.020 to 1.352 which should be compared to the virgin specimen ratio of 1.392. Higher ratio indicates higher ductility of the specimen and it is reflected directly on the shape of the specimen after failure as will be shown later.

In order to evaluate the effectiveness of each repair technique with regard to retaining the original load carrying capacity (yield and ultimate) of the specimens, fig. 7 shows the relative values of $(P_y)/(P_y)_o$, $(P_{ult})/(P_{ult})o$, and $(H.I.)/(H.I.)_o$ ratios for all specimens.

6.1. Yield load

With respect to the yield load ratio, all specimens, with the exception of S4 and S7, have shown higher average values than the virgin specimen. Both S1 and S6 have shown the highest increase of 12.5% than the original specimens, while S4 has shown a reduction of 4.8 %. On the other hand, the premature failure of bolts in S7 has prohibited the plasticity development in it.

One important notice in this regard is the variation of the yield load as the two specimens of each repair technique are compared. All test specimens have shown considerable consistent results with respect to the yield load except S3 which shows the higher variation (328.5 vs. 282.5 kN). This variation gives rise to the importance of the hole size for blunting the crack tip. As the hole size of S3 is 5 mm (which has been proven before by the author [7] to suffice for crack tip blunting) seems difficult somewhat to allocate, and thus resulting in a considerable variation of the yield load. This is also reflected on the yield load value for S1, S2, and S3. It is clear that the larger the hole size, the higher the yield load achieved in this repair technique as can be seen in table 1. This conclusion is limited to the yield load and the repair technique used for these specimens where the holes are filled with welding material.

6.2. Ultimate load

Unlike the yield load, only three specimens have showed an ultimate load equal to or higher than the virgin specimen. Those specimens are S2, S3, and S6 with a ratio of $(P_{ult})/(P_{ult})_o$ equal to 1.008, 1.009, and 1.084, respectively. It is worth mentioning that S1, which has shown one of the highest yield load, exhibited the one of the worst ultimate load values with a ratio of $(P_{ult})/(P_{ult})_o$ equals to 0.826. This can be attributed to the basic two

Table 1
Experimental test results

Specimen Designation	Specimen # 1			Specimen # 2			Average values		
	Yield load (Py) kN	Ultimate load (Pult) kN	Crack propagation location	Yield load (Py) kN	Ultimate load (Pult) kN	Crack propagation location	Yield load (Py) kN	Ultimate load (Pult) kN	P_{ult}/P_y
S1	331.0	340.5	O.C.L.	330.5	335.5	O.C.L.	330.8	338.0	1.022
S2	325.0	425.5	O.C.L.	326.0	399.5	O.C.L.	325.5	412.5	1.267
S3	328.5	454.5	O.C.L.	282.5	371.5	O.C.L.	305.5	413.0	1.352
S4	278.0	326.0	O.C.L.	281.5	343.0	O.C.L.	279.8	334.5	1.196
S5	330.0	337.5	O.C.L.	322.0	327.5	O.C.L.	326.0	332.5	1.020
S6	330.0	466.5	Outside	331.5	400.0	W.F.	330.8	433.3	1.310
S7	N.A.	303.5	B.F.	N.A.	316.6	B.F.	N.A.	310.1	N.A.

O.C.L.: Crack started and propagated at the Original Crack Location
Outside: the failure is outside the splice plates
W.F. : Weld Failure
N.A. Not applicable
B.F.: Bolt Failure

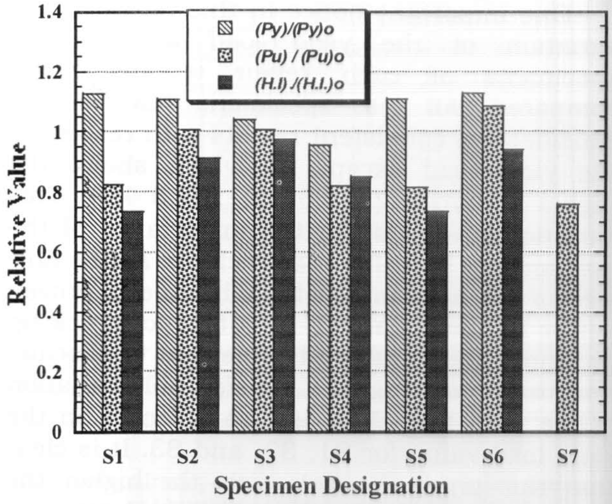


Fig. 7. Relative values for P_y, P_{ult}, and H.I. compared to virgin specimens.

concepts explained before for blunting the crack tip [7]. The larger hole diameter (15 mm in case of S1) has eased the stress concentration at the crack tip considerably, leading to the best opportunity for dislocation emission and higher yield load. However, the considerable reduction in the ligament due to large hole drilling, and the relatively weaker welding material has substantiated the considerable reduction of the ultimate load carrying capacity. On the other hand, the relatively smaller holes have resulted in less easing of the stress field at the crack tip, with higher ultimate load due to the relatively longer ligament. However, S1 has showed the lowest variation between the two specimens with very consistent results as compared to S2 and S3, this gives rise again to the difficulty associated with allocating the crack tip in case of small holes, which leads to the discrepancy in the results for S2 and S3.

Considering the welded splices for S6, which has shown the highest increases in the ultimate load, there has been also a considerable variation in the ultimate load (466.5 vs. 400 kN). This is mainly attributed to the mode of failure which is associated with failure outside the splice zone for the higher load as compared to the failure in the weld for the lower load.

The worst performance of all specimens, with respect to the ultimate load, has been related to the repair technique of S4 and S5, where for S4, the crack was not blunted while for S5, the weld was deposited directly to the crack faces without neither blunting nor grooving the crack faces. It is clear that these two preparation techniques for the crack are crucial for easing the stress field and ensuring the proper welding. Regarding the specimen S7, the premature failure of bolts has inhibited the proper conclusion for this type of repair technique.

6.3. Hardening index

All the previous comparisons are held between the absolute values of either the yield or load of the specimens to the virgin specimen in order to evaluate the effectiveness of each repair technique with regard to regaining the initial load carrying capacity. However, one of the most important factors is the ability of each individual technique to exhibit considerable hardening after attaining the yield load. This is expressed in this paper with the hardening index (H.I.), which is the ratio between the ultimate to the yield load. Although no deformation has been recorded during the experiments, it has been observed that for higher H.I., more plastic deformation has been achieved for the specimen as will be shown later. Unfortunately, none of the repairing techniques used in this study has achieved the same H.I. as the virgin specimen as can be depicted from fig. 4. The highest H.I. (0.972) has been recorded for S3, followed by 0.941 for S6 and 0.911 for S2. The worst of all has been for S1 (0.734) and S5 (0.733).

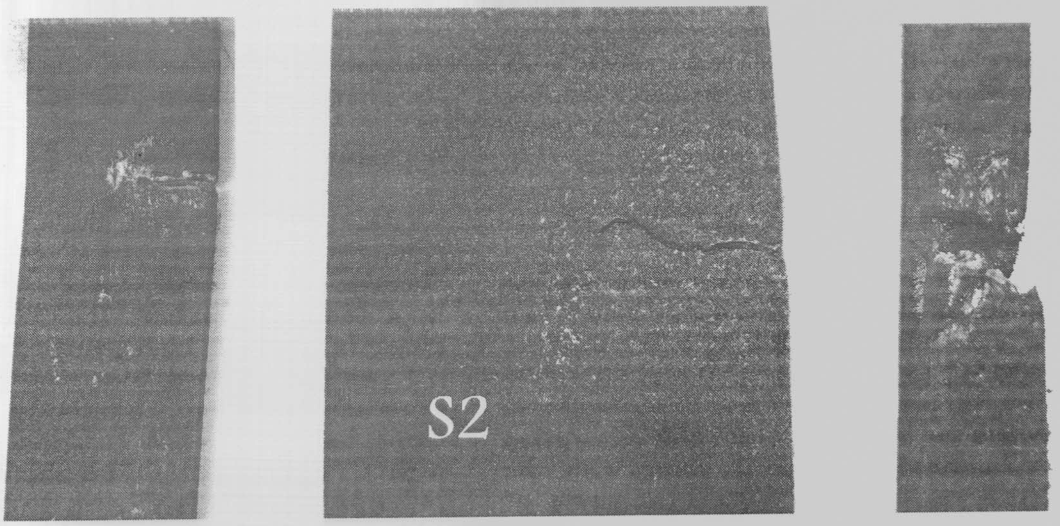
6.4. Failure modes

It has been observed that the mode of failure for most specimens is almost similar and can be described as the initiation and propagation of the original crack after attaining the peak load. For instance, fig. 8 through fig. 10 show the close up pictures for specimens S1, S2, and S3. For the three specimens, the failure crack started again at the location of the initial crack and propagated around the blunting hole. It is worth mentioning that S3 exhibited the most plastic deformation at failure amongst the three specimens, while S1 showed the lowest. This finding agrees well with the H.I. as explained before. On the other hand, both S4 and S5 showed very little plastic deformation with the final crack initiated from the same original crack as well as shown in fig. 11 and 12.

With respect to splicing techniques, fig. 13 shows the two specimens for S6-1 and S6-2 where a considerable plastic deformation has been observed for both, with the first one failing outside the splice zone. It is worth mentioning that the second specimen, where the failure was at the splice weld location, the crack started again at the blunted crack tip and propagated outward. For bolted splice, fig. 14 shows the failure shape of the specimen where very little plastic deformation has been observed.

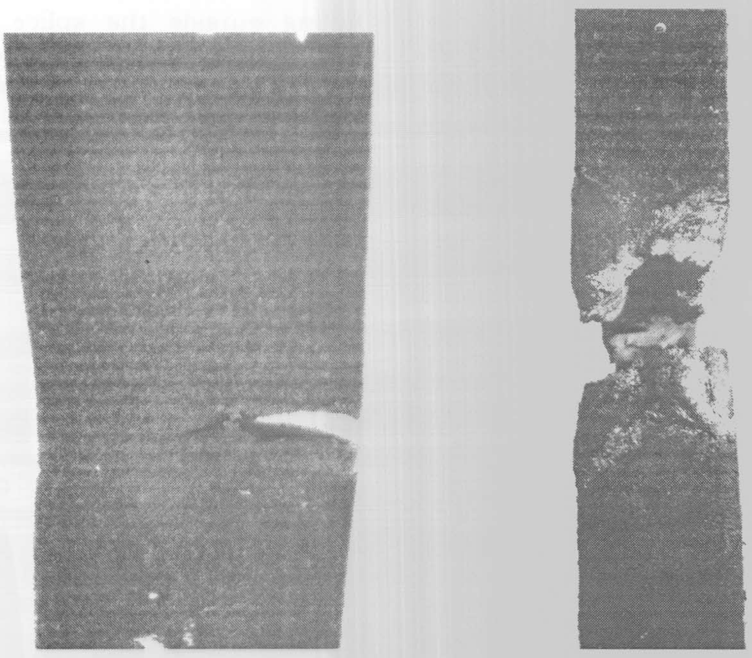
a) General view b) close-up for the crack c) side view

Fig. 8. Specimen S1 after failure.



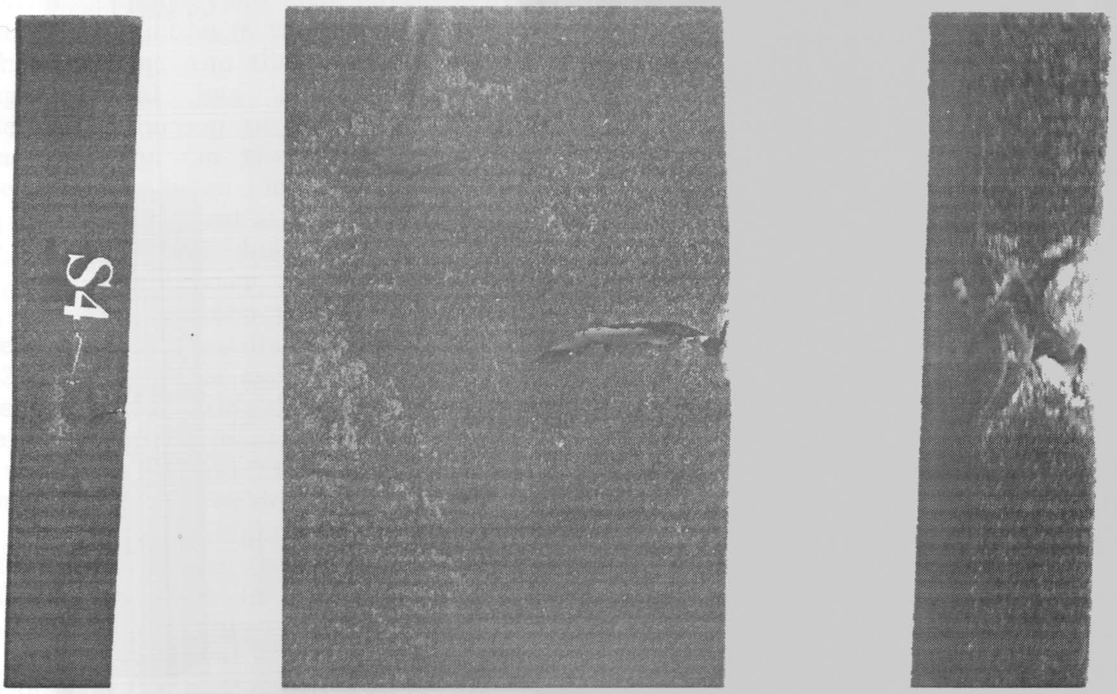
a) General view b) close-up for the crack c) side view

Fig. 9. Specimen S2 after failure.



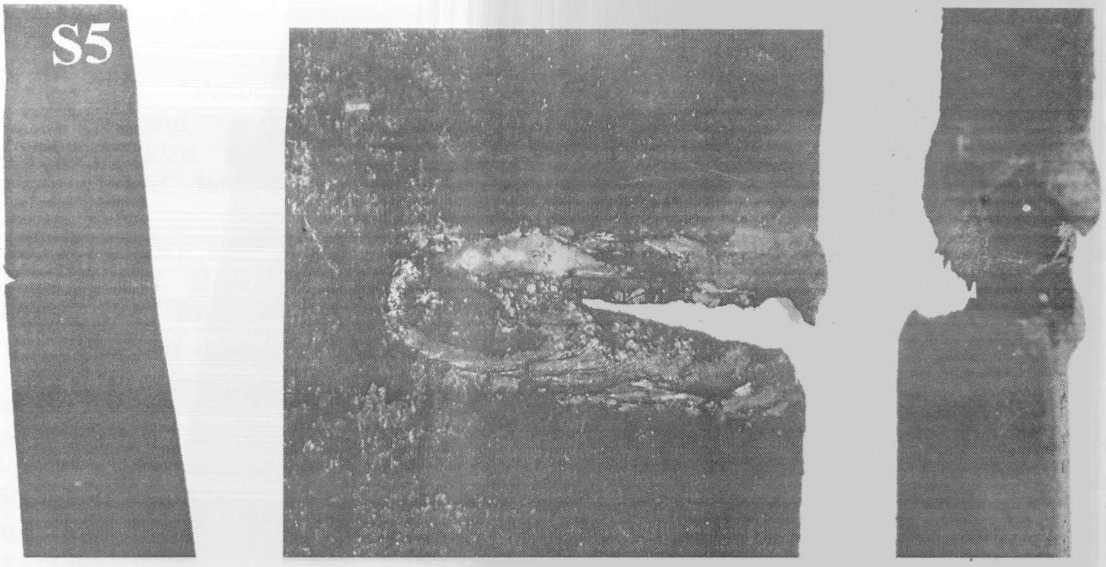
a) General view c) side view

Fig. 10. Specimen S3 after failure.



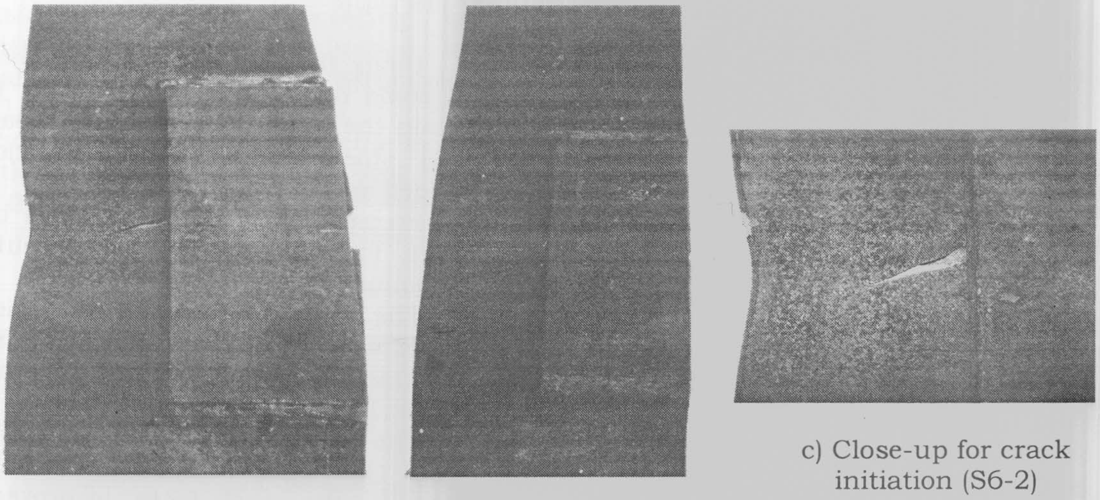
a) General view b) close-up for the crack c) side view

Fig. 11. Specimen S4 after failure.



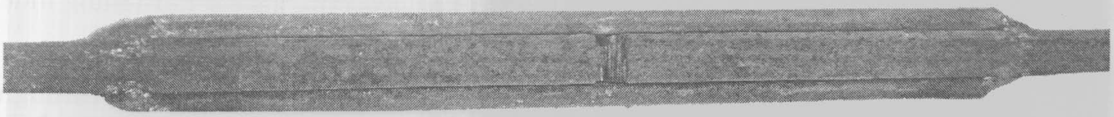
a) General view b) close-up for the crack c) side view

Fig. 12. Specimen S5 after failure.

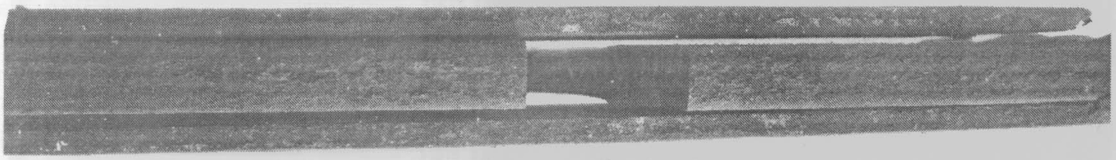


a) General View for S6-2 a) General View for S6-1

c) Close-up for crack initiation (S6-2)



d) side view for S6-1



e) side view for S6-2

Fig. 13. Specimens S6-1 and S6-2 after failure.

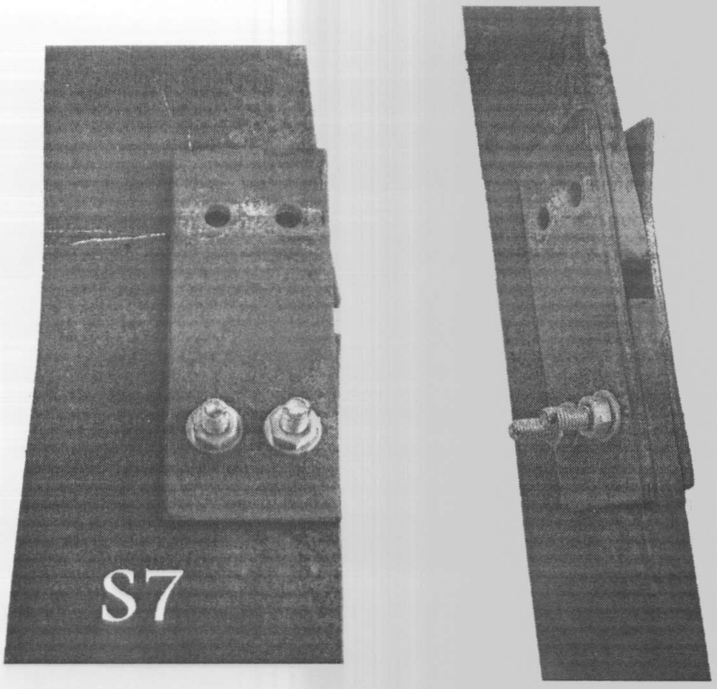


Fig. 14. Specimen S7 after failure.

7. Conclusions

Based on the experimental study in this paper regarding the evaluation of certain repair techniques for cracked steel components, the following conclusions can be drawn. All these conclusions are limited to the techniques and methods used in this study and can not be generalized to all cases. The conclusions are classified according to the repair technique, as follows:

a. Direct welding of the crack face:

1. Blunting the crack tip to ease the stress field is a crucial technique which should be implemented in any repair job.
2. The size of the hole affects the load carrying capacity of the repaired component significantly. Larger holes (15 mm) result in higher yield load while smaller holes result in lower the yield load, however, the results are reversed for the ultimate load.
3. More consistent results are obtained for larger hole diameter, and larger variations have been recorded for smaller hole diameter. This gives rise to the difficulty associated with locating the crack tip in case of smaller holes.
4. Using the Gas Metal Arc Welding (GMAW) in some repair jobs is practically possible to retain the initial load carrying capacity as the CO_2 shield reduces the distortion of the welded specimens significantly.
5. Preparation of the crack faces by grooving them for applying double V butt weld is recommended.
6. The most successful technique using direct welding of the crack faces is to groove the crack faces and to blunt the crack tip with a hole 10 mm or less.
7. The direct application of welding (even with GMAW), without either blunting nor grooving the crack faces, is proved to fail in retaining the ultimate load carrying capacity, and possess the lowest hardening index.

b. Splicing the crack wake:

1. Splicing the crack wake through welded splices using GMAW is efficient in retaining both the load carrying capacity and the ductility of the virgin specimen provided that the weld thickness should be designed such that the failure is outside the splice zone.
2. More work is needed for bolted splices to ensure the achievement of proper load carrying capacity and the associated ductility.

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