Repair of Existing Steel Moment Frame Buildings Damaged from Earthquakes Using Fracture Tough Weld Overlays

WARNER SIMON, JAMES ANDERSON, JACK COMPTON, WALTER HAYES, and PETER MARANIAN

ABSTRACT

This paper reports the first phase of a research and testing effort by a volunteer group of Metallurgists, Structural Engineers, Testing Engineers, and Welding Engineers who have developed methods of repairing existing earthquake damaged steel moment frame connections, using fracture tough weld overlays enabling the joint to be considered as a Dynamic Load Weld (DLW). This follows the well reported damage to Steel Moment Frame Buildings observed following the January 17, 1994 Northridge Earthquake. Subject to more research and testing, the methods may eventually prove suitable for modification of existing steel moment frame buildings and new construction, along with application in other industries.

INTRODUCTION

During the course of the last three years, a group of Metallurgists, Structural Engineers, Welding Engineers and Test Engineers have been carrying out research and testing and soliciting knowledge from both within and outside of the industry on the development of effective and economic repairs of damaged steel moment frame buildings using weld overlays.

Research and testing by the DLW Task Group, led by Dr. Warner Simon, has resulted in repair methods being developed using weld overlays to address the weld and material issues associated with the problem in an economic manner. This group is a continuation from other groups applying fracture mechanics to other industries, e.g. Aerospace (examples, the B1 supersonic aircraft, the Challenger space shuttle, and many welded aircraft components) containing reliable welds under complex dynamic load conditions. Weld overlays use a tough weld designed to take, if necessary, the full dynamic load. In this way, redundancy is provided to compensate for weld damage. The technical advantages of overlays, without significantly gouging the original weld, outweigh the economic advantages, as secondary repairs and gouges frequently cause secondary defects and secondary stresses.

The approach of using overlays, has a rather interesting history. The work started with the British Admiralty in Scotland in response to a history of catastrophic failures in the naval and offshore oil industries, caused by inattention to adequate materials, and the use of additives to speed up the welding process that were incompatible with the material. The British Admiralty conducted extensive research into such commercial materials prone to fracture initiation and propagation that yielded positive results, i.e. a fracture resistant layer using the Gas Tungsten Arc Weld (GTAW). Commonly used explosion bulge tests were replaced by quantifiable hull toughness element tests which revealed weld quality with significant economies (Bird and Sumpter, 1992).

In the current study, small component tests were carried out to investigate the dynamic capability of the welds and subsequent full size beam to column connection tests were done to verify the overall elastic and ductile inelastic behavior of the sub-assembly.

This paper is a condensed version of a more comprehensive report (Simon, Anderson, Compton, Hayes, and Maranian, 1998).

DISCUSSION

As has been documented in many publications, e.g. SAC (1995); Bertero, Anderson, and Krawinkler (1994); Maranian (1997), typical damage associated with the Northridge earthquake resulted from fracture initiation in the root of the welds made with weld metal having low fracture toughness. In many cases damage appears to have often occurred at stress levels well below yield since damage to exterior architectural elements (window walls, precast, etc.) invariably was not significant (Maranian, 1997). While the fractures mainly initiated in the root of the weld, they propagated in all directions such as through the weld metal, through the parent

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metal, or in whatever direction offered the least resistance. Our initial research suggested that the pre-Northridge welding procedures and inspection practices, combined with a lack of control of the brittle to ductile transition temperatures for the materials used, contributed to the weld failures. In addition it was found that there was limited understanding of the significance of strain rate, residual stresses, notch effects, weld defects, welding effects on parent metal and compatibility chemistry of the joining materials.

Following the Northridge Earthquake, significant improvements have been made in the joint design for new construction, including removal of the back-up bar and increase in weld notch toughness along with modification to the connection design, such as the addition of cover plates, haunches, reduced beam sections, etc. However, changes in the weld joint design only have not in general resulted in significantly improved performance of the pre-Northridge connection.

Some questions and concerns regarding parent metal, which may be pertinent to the overall behavior of connections, are discussed elsewhere (Simon et al., 1998).

PRINCIPLE OF THE DLW OVERLAYS

The principle of the DLW overlays is essentially to deposit a fracture tough weld overlay thus enhancing the performance of the whole assembly. The DLW overlays are such as to significantly reduce the potential for crack initiation caused by the numerous defects in the weld metal, heat affected zone (HAZ) and base metal. The weld overlay is required to perform to its specific load requirements using the most suitable welding process and inspection procedure to provide a high dynamic load resistance. With the presence of the overlays, defects are distanced from the surface thus reducing the stress intensity factor and the potential for crack initiation. It should be recognized that fracture initiation, in addition to location, also depends upon the stress state, stress range, size, shape and orientation of the discontinuity and toughness of the material. In the unlikely event of a crack initiating and propagating from an internal defect, the overlay is intended to have sufficient fracture toughness to arrest the propagation of the crack.

Many engineers have questioned the reliability of nondestructive testing methods to detect defects/damage. The authors are aware of a repair project where core samples through the welds showed flaws which were previously undetected by ultrasonic inspection. In fact, E70T-4, the commonly used flux core arc weld self-shielded (FCAW-ss) electrode in existing buildings, has no minimum toughness requirements. This, along with improper welding procedures, with a conglomeration of non-detectable defects can render the weld more susceptible to brittle failure unless protected by weld overlays. It should be mentioned that some higher grade FCAW-ss electrodes, with improved toughness and proper welding procedures, have apparently been found capable of absorbing some dynamic loads (Kaufman, Xue, Lu, and Fisher, 1996).

The quality of the overlay is primarily dependent upon the purity of the filler metal and control of trace elements before and during deposition of the weld along with welding parameters and operator qualifications. Generally, dependent upon specifications, welding procedures, welding parameters and operator qualifications, the Gas Tungsten Arc Weld (GTAW) process and the Shielded Metal Arc Weld (SMAW) process, can produce, respectively, very high and medium quality welds. Although GTAW is the preferred process and some of the earlier testing included the GTAW process, the SMAW process is more readily used in the industry and was therefore the primary process used in the development of the repair overlays. The FCAW-ss process, at the time of testing, based upon many discussions with several welding engineers, and from research into literature (Lancaster, 1992 and Cary, 1979) was thought not to have adequate crack arresting properties. However, small component and full size testing of weld overlays, using high quality FCAW-ss has recently been carried out. At the time of writing, the results have not been fully analyzed but appear encouraging. Results will be reported in future publications.

An important concern in the research and testing was the problem of mixing processes and dilution which were noted by the Federal Emergency Management Agency (SAC, 1995). The small component drop weight, low cycle fatigue tests, and metallographic tests verified the integrity of the interface and the control of dilution. Some degradation of toughness can occur as described by Johnson and Quintana (1997) and Blodgett, Funderburk, and Miller (1997). However, sufficient toughness still remains and particularly in the outer weld layers. This also appears to have been confirmed in other references (Jorgenson, 1995; Ojdrovic and Zarghamee, 1997).

As has been demonstrated by Richard, Partridge, Allen, and Radua (1995), very high stress and strain concentrations can occur in the beam flange weld with correspondingly higher demands on the ductility and strain rate of the parent metal, heat affected zone (HAZ) and weld material. The profiles of the weld overlays were configured to assist in reducing these demands throughout the joint.

TYPES OF REPAIRS

Typical Classes

It was recognized that it was necessary to classify the various types of repair. These were classified as follows:

CLASS A. If dynamic joint efficiency is under 50 percent or has not been determined, apply a maximum overlay with SMAW to supplement the joint deficiency to arrive at a joint which will take the full load demand and existing column flange heat affected zone.

CLASS B. Gouge out the entire weld and column flange heat affected zone and replace with SMAW and add a fillet weld.

CLASS C. If the dynamic joint efficiency is over 50 percent, apply a minimum overlay with SMAW to supplement the joint deficiency.

CLASS D. Failure of a major structural element, e.g. column separation, replace the failed element using SMAW for repair.

CLASS E. Overlay with premium fracture resistant filler metal using a premium welding process, e.g. GTAW or PAW overlay and SMAW transition layer, if required.

Class A, B, and C are shown in Figures 1, 2, and 3, respectively.

Class B represents the conventional repair typically being carried out on major cracks in beam flange welds on repair projects in Los Angeles. It should be noted that some repairs have used high quality FCAW-ss in lieu of SMAW.

Classes A and C represent repairs using weld overlays. Class A is intended to be used for significant NDT indications in the beam flange weld. Class C is for minor indications (NDT) in the beam flange weld. The sequencing of the welds, as shown in the Figures 1, 2, and 3, is such as to minimize the build up of residual stresses.

Class D primarily represents column flange and web cracking and is beyond the scope of repair using weld overlays.

Additional Classes to Address Lamellar Tearing

Additional classifications A1, B1 and C1 (see Figures 4, 5 and 6) show variations of the repair methods for applications to mitigate the potential for lamellar tearing. The additional procedures involve partial removal of about ¼-in. of the column flange, including the heat affected zone, and the

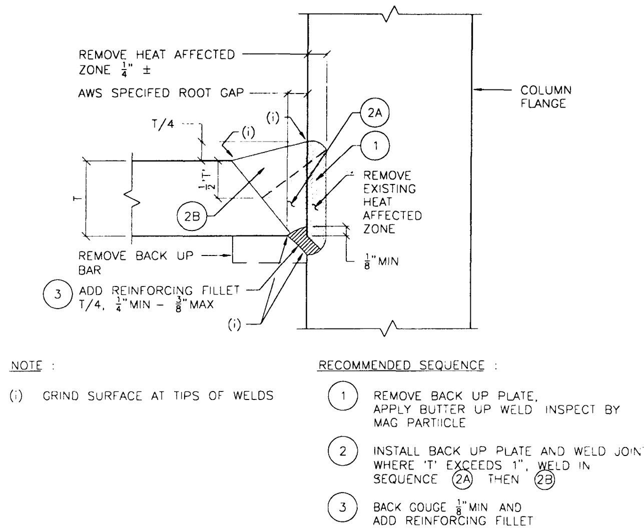


Fig. 2. Repair-crack thru beam flange Class B.

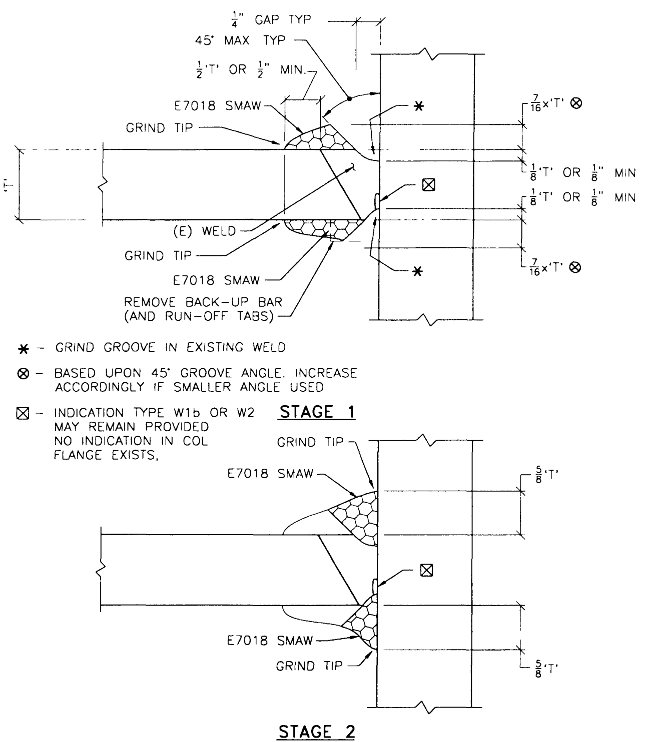


Fig. 1. Class A repair using SMAW.

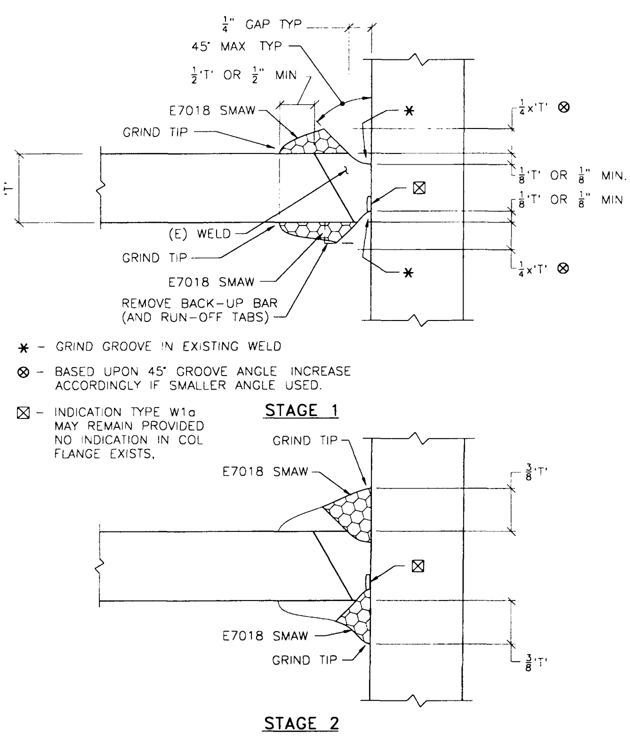


Fig. 3. Class C repair using SMAW.

application of a buttering layer. The application of a buttering layer has been used in steel fabrication for many years and is well documented (Farrar et al., 1975; Farrar and Dolby, 1972; AISC, 1973; ASME, 1995). The use of buttering the column flanges is recommended where the material is suspected of being susceptible to lamellar tearing. A good quality E7018 electrode has been shown to result in satisfactory performance. Lamellar tearing has been encountered during construction in older steels, e.g. Atlantic Richfield Plaza Building in Los Angeles 1973 (Kaminetzky, 1991). At this point in time, whether lamellar tearing can be a possible mode of future damage in an existing column, is an area where further research appears necessary.

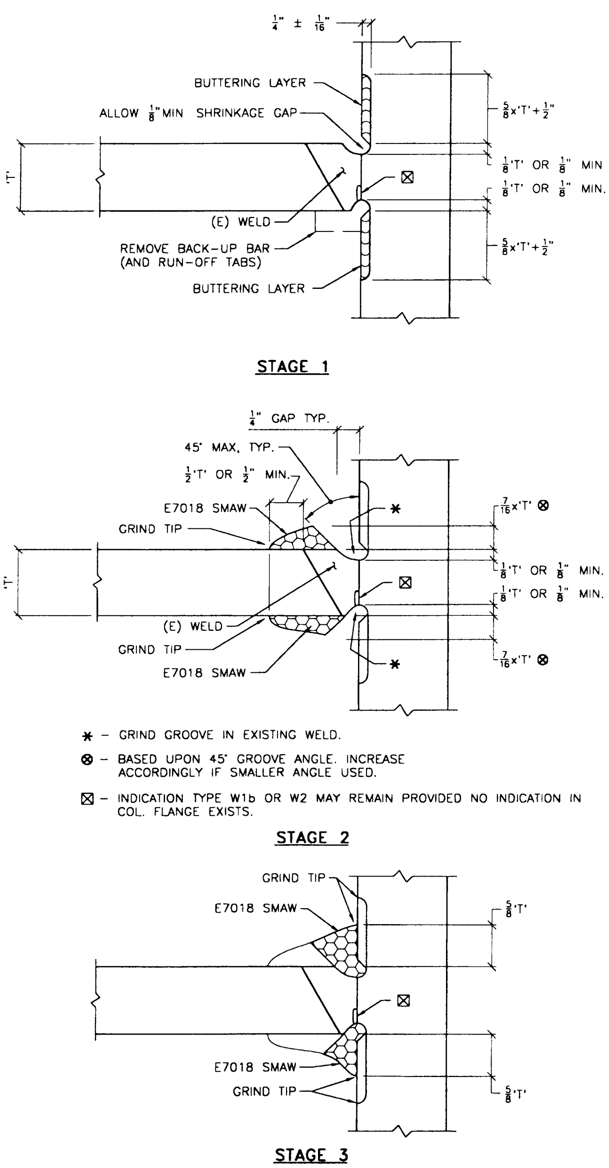


Fig. 4. Class A1 repair using SMAW with paliative application to mitigate potential for lamellar tearing.

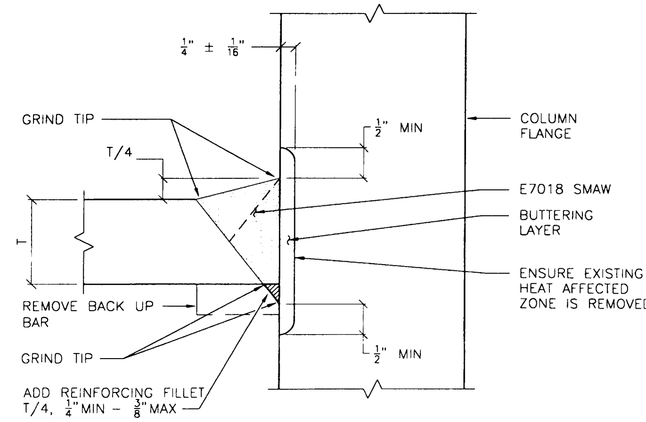


Fig. 5. Repair-crack thru beam flange Class B1 with paliative application to mitigate potential for lamellar tearing.

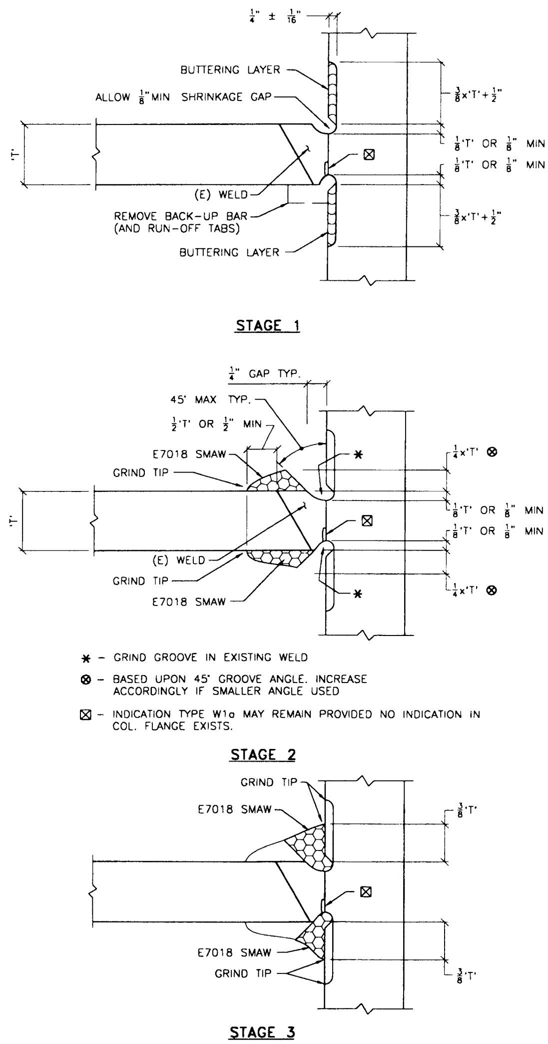


Fig. 6. Class C1 repair using SMAW with paliative application to mitigate potential for lamellar tearing.

SMALL COMPONENT TESTS

The testing approach adopted was to first carry out small component tests. The standard Charpy test, although useful for studies on transition temperatures on individual materials (i.e. parent metal and weld-metal), does not apply to a composite joint. Therefore it was necessary to develop a test approach that could better accomplish this and this led to the adoption of drop weight and low cycle fatigue tests. The drop weight test was developed at the Naval Research Laboratory in 1952 and has been used extensively to investigate the conditions required for initiation of brittle fractures in structural steels. The test has been an important factor in discovering the cause of catastrophic failures. In our testing, we adopted "tee" specimens in lieu of horizontal plate specimens used in conventional drop weight tests per ASTM E208-95a. Figure 7 shows a drop weight test on a pre-Northridge weld specimen with failure in the weld.

An extensive investigation was carried out to find out if internal defects could initiate fracture. Test results at Lehigh University implied that an internal defect could cause dynamic instability (Kaufman et al., 1996); a DLW layer will counteract the instability. For the drop weight and low cycle fatigue tests carried out by the task group, artificial implants of concrete and ceramic were inserted into the weld and tested. Figure 8 shows a low cycle fatigue test specimen with a Pre-Northridge weld having failure in the weld. In all these tests, the implant had no bearing on the fracture path, thereby confirming the theoretical investigations of fracture initiation.

Test specimens were then made with the fusion between the existing flux core arc weld and the column flange plate separated (See Figure 9). This was accomplished by sawing through the flux core arc weld at the face of the column flange. Overlays using the SMAW process with no preheat were then applied over the original joint simulating a large defect (Figure 9). The specimens were then tested by drop weight and low cycle fatigue tests. Figure 10 indicates the significant bend achieved by the specimen with overlays and simulated large indication when subjected to the drop weight test. The

Fig. 7. Drop weight test on a pre-Northridge weld.

Fig. 8. SMAW overlay over FCAW core with ceramic implants.

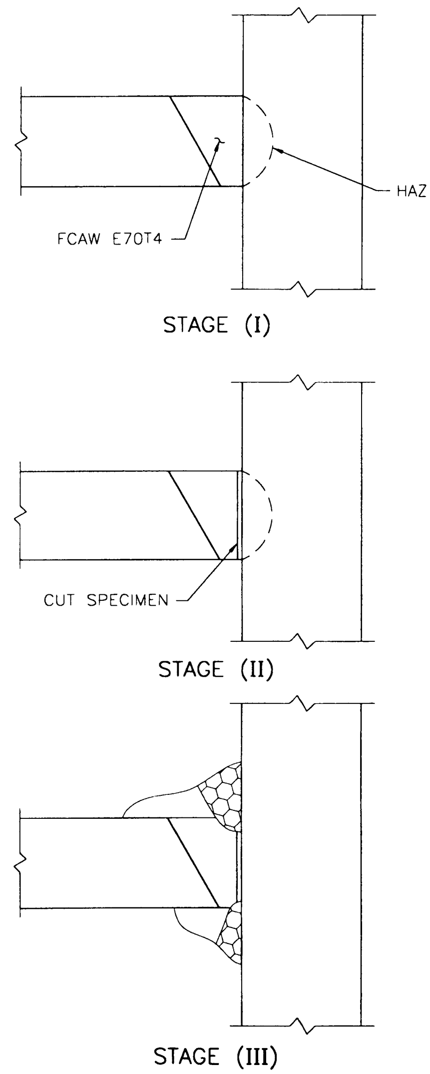


Fig. 9. Test to investigate potential for crack propagation.

Table 1. Summary of Low Cycle Fatigue Tests for College of Canyon Specimens						
Specimen No.	Size	Stress Range	Load Max. Pounds	Load Min. Pounds	No. of Cycles	Failure Location
10B	1" x 0.152"	50 ksi tension to 30 ksi comp.	–7.623	4,578	87,500	Grip/weld
10C	1" x 0.196"	50 ksi tension to 30 ksi comp.	–9,655	4,964	4,964	Parent Metal
10D	1" x 0.249"	50 ksi tension to 30 ksi comp.	–12,275	7,184	7,184	Parent Metal

results of the low cycle fatigue tests, with a stress range of –50 ksi (tension) to +30 ksi (compression) at 5 cycles per sec, are shown in Table 1 with the specimens attaining in excess of 4,900 cycles before failure occurred.

One of the questions that arose was, if there was a potential for cracks to penetrate the original HAZ and continue through the column flange. Specimens with both vertical and horizontal cracks (cruciform) were then fabricated (See Figure 11). As before, no preheat was applied. The specimens used E7018 overlays with dimensions considerably below the class A details developed by the group. However, the tests still performed quite well with no crack propagation from the defects. Table 2 indicates the results of the low cycle fatigue tests with the specimens attaining in excess of 600 cycles before failure occurred. Figure 13 shows the drop weight test,

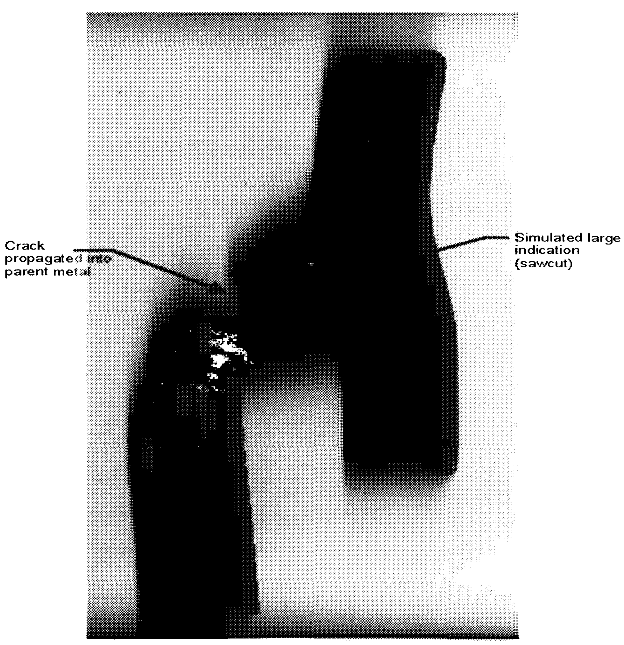


Fig. 10. Drop weight test (down with root gap on top) on overlay repair.

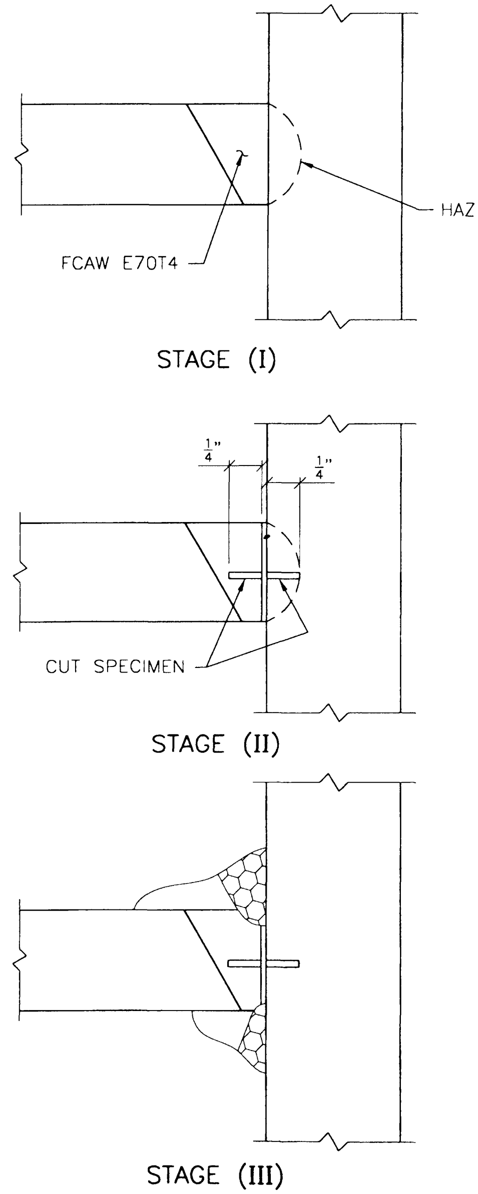


Fig. 11. Test to investigate potential for crack propagation thru column flange.

Table 2. Summary of Low Cycle Fatigue Tests for Accurate Weld Testing Laboratory Specimens						
Specimen No.	Size	Stress Range	Load Max. Pounds	Load Min. Pounds	No. of Cycles	Failure Location
1N2-3	1" x 0.2"	50 ksi tension to 30 ksi comp.	−10,000	6,000	843	Weld
1N2-4	1" x 0.2"	50 ksi tension to 30 ksi comp.	−10,000	6,000	606	Weld
1N2-5	1" x 0.2"	50 ksi tension to 30 ksi comp.	−10,000	6,000	1,181	Weld

Notes:
1. All specimens tested at 5 cycles per sec. from 50 ksi (tension) to 30 ksi (compression)
2. Tests carried out by Metals Technology

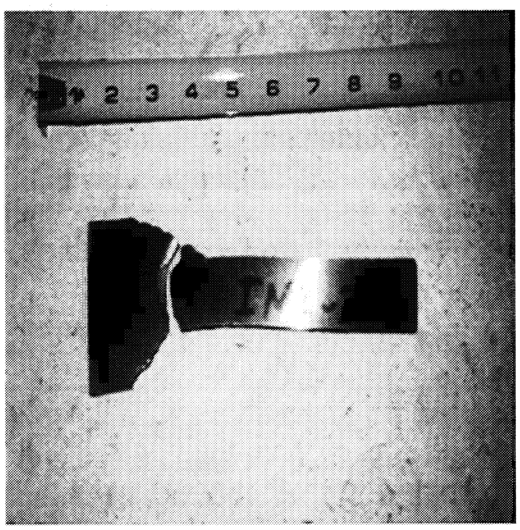


Fig. 12. Low cycle fatigue test on overlay repair with simulated large defect.

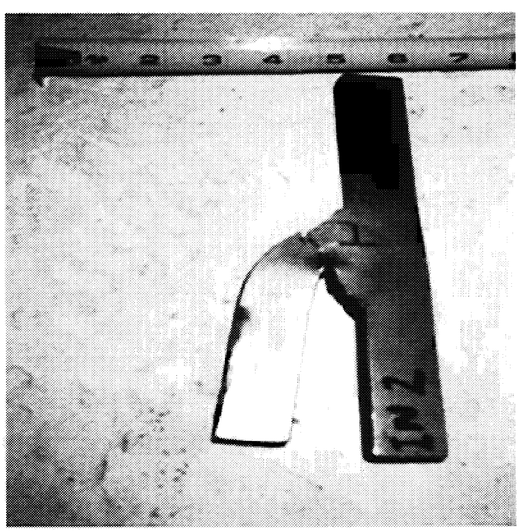


Fig. 13. DWT test (down with root gap on top) on overlay repair with large cruciform defect (Accurate Weld Testing Laboratory specimen).

again with the specimen achieving a significant bend and with failure well away from the large internal defect.

FULL SIZED WELD OVERLAY TESTS

As part of a testing program sponsored by the National Science Foundation (Anderson and Duan, 1998), two full connection specimens were tested to demonstrate the performance of the overall system. The tests were carried out in accordance with ATC 24 (ATC, 1992). Test specimen details and configuration are shown in Figures 14a and 14b and the results of the tests are summarized as follows:

Specimen 1

General Description of Repair

The material specimen was a W16×77 column with a W21×68 beam and no web doubler plate in the panel zone.

This specimen was initially tested in the "as received" condition with the welded connection representative of those used prior to the Northridge earthquake. Back up plates were used and the beam flanges were welded to the column flange with FCAW-ss using E70 T-4 wire. During this test, the specimen failed at a displacement of 2 in. which is representative of a 3 percent total rotation (1.5 percent plastic). A crack initiated in the weld at the bottom flange of the beam and propagated vertically through the weld and part of the column flange. Ultrasonic testing confirmed that the crack was primarily vertical and that it encompassed part of the column flange. Ultrasonic testing of the weld at the top flange of the beam indicated that it was intact with no cracking. This offered an excellent opportunity to test the use of a weld overlay for a Class A repair which would leave more than half of the crack in place under the overlay.

The crack at the bottom flange of the beam was repaired in the laboratory following the detail for a Class A type of repair shown in Figure 15. The existing crack was excavated using an air arc. It can be seen that part of the column flange was removed to encompass all of the crack. On the underside of the beam flange, the backup bar was removed and part of the existing weld was removed by air arc exposing the crack. Approximately 0.125 in. of the crack were removed by air arc from the top and bottom of the existing weld, leaving 0.375 in. of the crack in place. At the top flange of the beam, the backup bar was removed and the weld backgouged according to recommended practice. Since the top flange weld was tested and found to be sound, no action was taken on the upper side of this weld (see Figure 16).

Overlays exceeding the minimum requirements of the Class A overlay were applied to both sides of the excavated connection at the bottom flange of the beam, using 26 passes for the upper side and 15 passes for the lower side.

All overlay welding was done using SMAW with E7018 electrodes. At the top flange of the beam, an overlay weld was applied to only the underside of the flange using 10 passes. This simulated a repair without removal of the concrete slab above the top flange, which is the typical condition occurring in buildings.

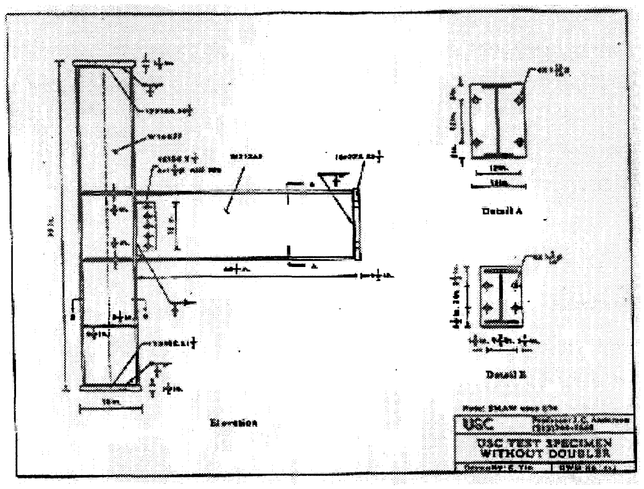


Fig. 14a. Test specimen detail.

Fig. 14b. Test configuration.

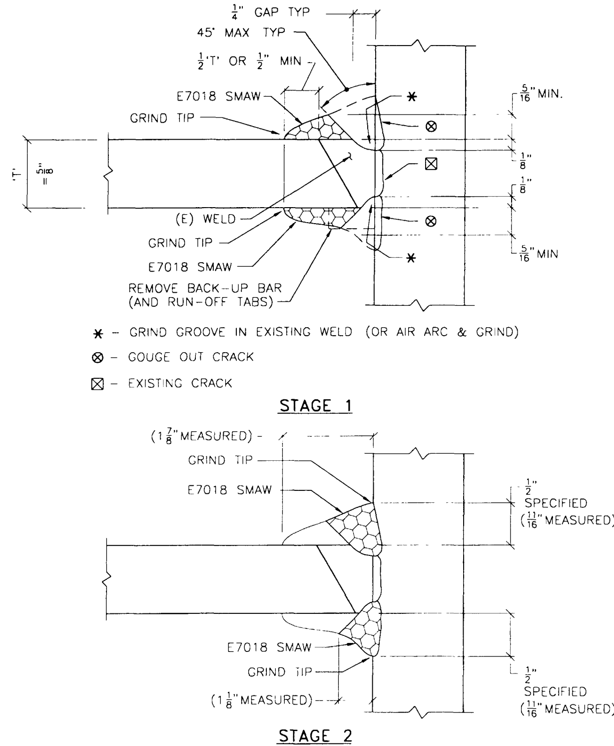


Fig. 15. Bottom flange overlays (Class A) full size test specimen no. 1.

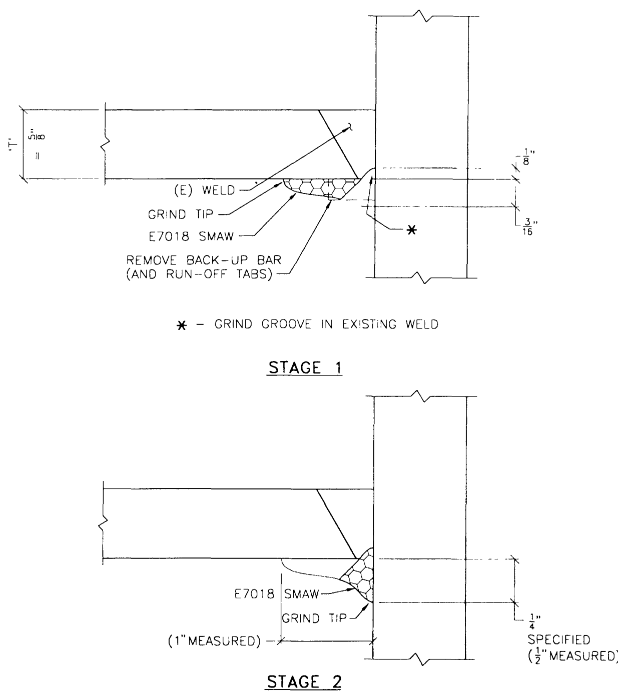


Fig. 16. Top flange overlay full size test specimen no. 1.

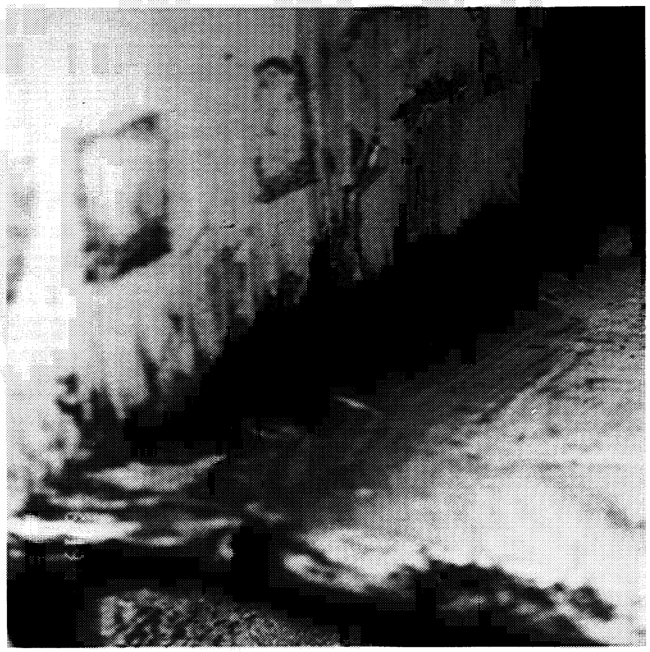
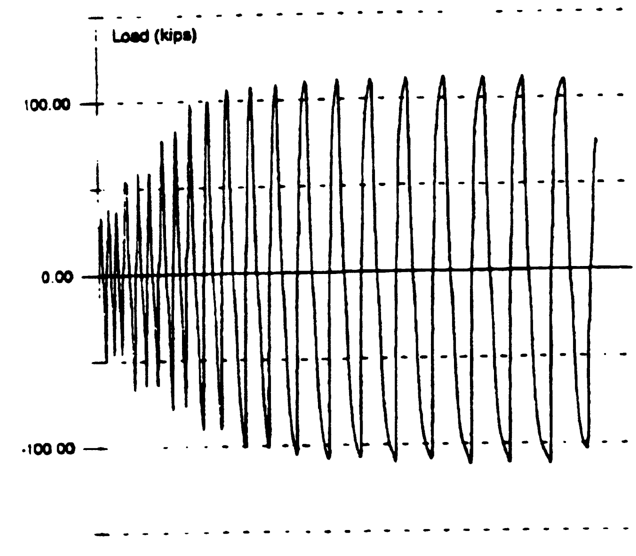
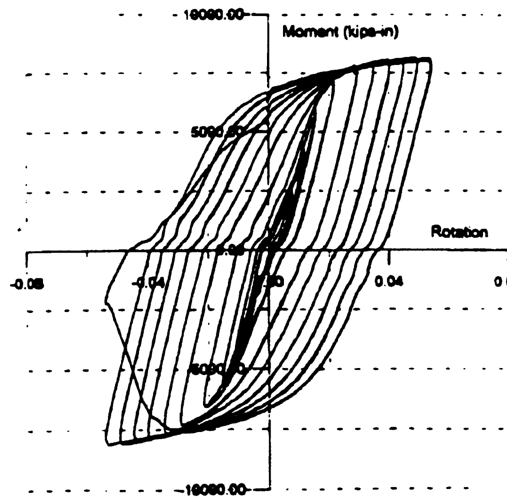


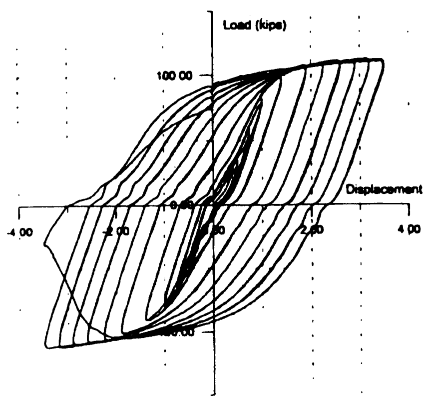
Fig. 17. Crack in top flange of beam.
Full Size Test Specimen No. 1.



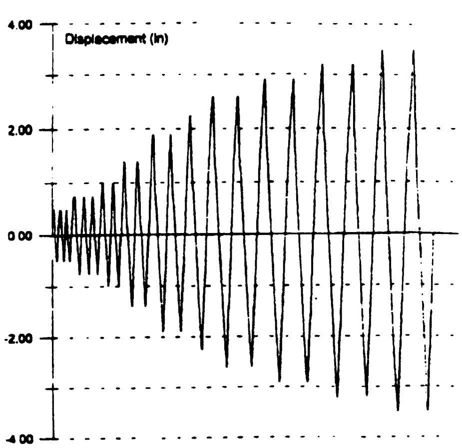
(c) Beam Load History



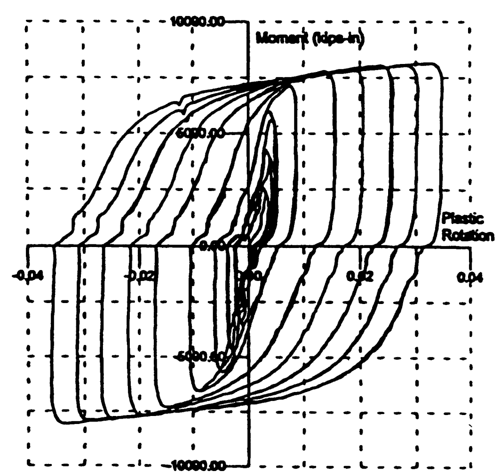
(d) Moment vs. Rotation Hysteresis



(a) Load vs. Displacement Hysteresis



(b) Displacement History



(e) Moment vs. Plastic Rotation

Fig. 18. Cyclic performance full size test, specimen no. 1.

Specimen Performance

Specimen performance was excellent. The specimen reached a total rotation of 5.5 percent. It was observed that most of the deformation was occurring in the panel zone. During the second cycle at 5.5 percent total rotation a crack occurred in the top flange of the beam at the interface of the weld and the parent metal (Figure 17). At the same time a crack (slit) had started from the web cope and propagated along the k-line at the bottom flange of the beam. However, both of these slits did not propagate rapidly and appeared to have little influence on the overall connection behavior. Failure occurred when the crack in the top flange of the beam propagated from the center to the sides.

The load versus displacement hysteresis, shown in Figure 18a, indicates a peak displacement of 3.5 in. and very ductile behavior. The history of the applied displacements, shown in Figure 18b, indicates 21 cycles of increasing displacement. The corresponding history of the applied load at the beam tip, shown in Figure 18c, indicates no unloading of the specimen until the last cycle when failure occurred. The moment versus rotation curve (Figure 18d) shows the maximum total rotation of 5.5 percent. If 1.5 percent is taken as the elastic rotation, the total plastic rotation is approximately 4 percent, as shown in Figure 18e, which is well above current acceptance criteria.

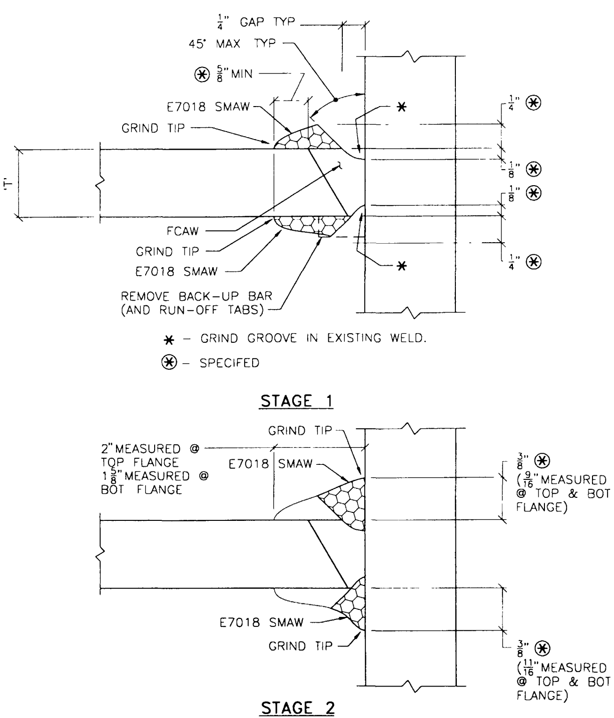


Fig. 19. Top & bottom flange overlays full size test specimen no. 2.

Specimen 2

General Description of Repair

The material specimen was a W16x77 column with a W21x68 beam and no web doubler plate in the panel zone.

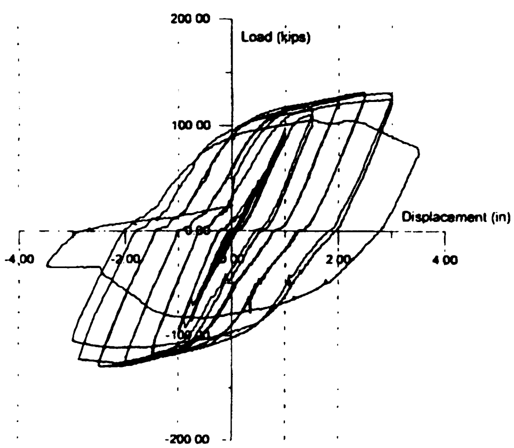
This specimen was not tested prior to applying the weld overlays and no defects were known to be present in the existing FCAW-ss welds. The configuration is identical with specimen #1 with the exception of the addition of a web doubler plate in the column which extends 8 in. above the top continuity plate and 8 in. below the bottom continuity plate on one side. This specimen represents a field upgrade of a connection made with FCAW-ss and E70 T-4 electrodes. The overlay procedure is representative of a Class C overlay which is shown in Figure 19. Backup bars at the top and bottom beam flanges were removed and the root of the weld was backgouged per recommended practice. Overlays exceeding the minimum requirements of the Class C overlay were applied to both sides of the top and bottom flanges of the beam. All overlays were done using SMAW with E7018 electrodes. Actual thickness of overlays applied were significantly thicker than specified. Since the overlay weld filled approximately half of the web cope, the remaining opening was plug welded in an effort to reduce the possibility of a secondary failure emanating from the web cope. This was considered, subsequent to the tests, not to have been good practice. (Please see comment in the Conclusions below)

Specimen Performance

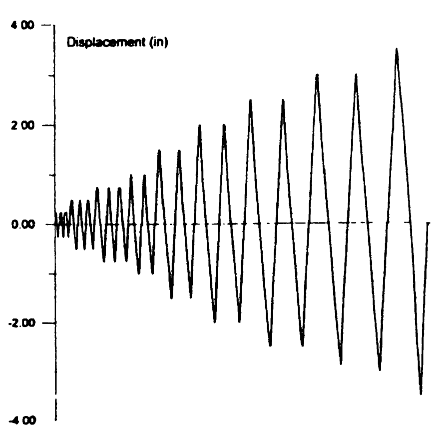
Specimen performance was very encouraging. The specimen was able to sustain 20 cycles of increasing displacement and reached a total rotation of 4.7 percent before starting to unload. At a tip displacement of 2.5 in. (3.9 percent total rotation) small horizontal cracks began to develop in the top k-line area and in the bottom k-line area of the beam web. At both locations the plug weld in the web cope cracked and the k-line cracks propagated from the web copes. During the first cycle at a tip displacement of 3 in. (4.7 percent total rotation) significant buckles began to form in the beam flanges about 4 in. at the top and about 10 in. at the bottom from the face of the column. This causes the specimen to start to unload as mentioned previously.

During the first cycle at a tip displacement of 3.5 in. (5.5 percent total rotation), a severe buckle formed in the top flange of the beam about 5 in. from the face of the column. This caused a separation of the flange and the web. This in turn caused the horizontal crack at the top k-line to extend almost 7½-in. from the edge of the web cope. At the bottom flange, the horizontal crack extended approximately 3½-in. from the edge of the web cope. On the down stroke, the flexing of the buckled top flange caused a crack to occur and propagate across the flange (Figure 20). With the fracture of the top flange, load was transferred to the web causing yield-

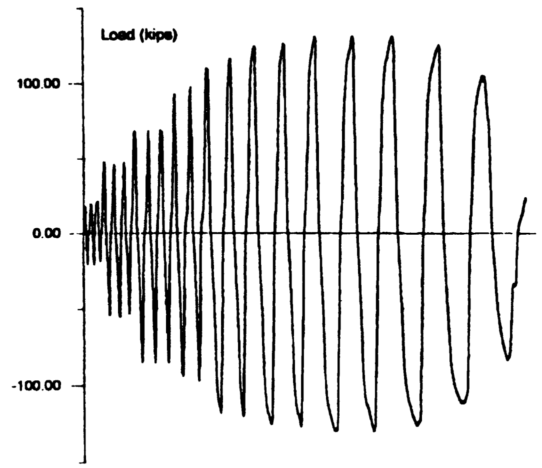
Fig. 20. Top flange failure (away from overlay) full size test specimen no. 2.



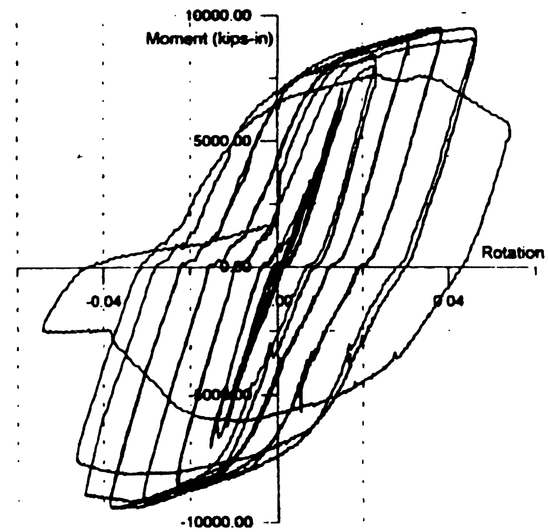
(a) Load vs. Displacement Hysteresis



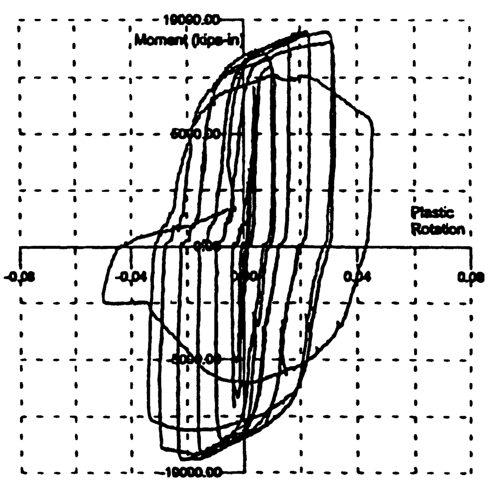
(b) Displacement History



(c) Beam Load History



(d) Moment vs. Rotation Hysteresis



(e) Moment vs. Plastic Rotation

Fig. 21. Cyclic performance full size test, specimen no. 2.

ing around the upper three bolts. Yielding of the top and bottom beam flanges extended a distance of 21 in. from the face of the column.

The load versus displacement curve for the specimen is shown in Figure 21a. It indicates that the specimen was able to reach a tip displacement of 3 in. (4.7 percent total rotation) prior to the significant unloading that occurred on the first cycle at 3.5-in. displacement. It can be seen that during the two cycles at 3.0-in. displacement, the specimen is starting to unload on the down stroke cycles. The corresponding history of the applied displacement is shown in Figure 21b and indicates the 20 cycles that were attained. The cyclic loading history at the beam tip is shown in Figure 21c and clearly indicates that the specimen is starting to unload during the last three cycles due to the buckling of the beam flanges. The moment versus total rotation curve, shown in Figure 21d, indicates a total rotation of 4.5 percent prior to significant unloading. Figure 21e shows that the total plastic rotation exceeds 3½ percent which is well above current acceptance criteria.

SUMMARY

The small component specimens, utilizing SMAW welded overlays, with vertical and with cruciform defects, attained large deformations before fracture when subjected to the drop weight test. Although there was very slight propagation of the internal defects, fracture occurred elsewhere, typically away from the internal defects.

The small component specimens, utilizing SMAW welded overlays and with vertical defects, tested by low cycle fatigue tests, exceeded 600 cycles before fracturing. Again fracture did not initiate at the internal defects.

The two full size beam column tests showed excellent performance. Specimen 1, with the significant rotation occurring in the panel zone, failed at the top flange from the web cope area in the parent metal (away from the overlay), to the heat affected zone at the top side of the beam flange, which did not have an overlay. At the bottom flange, where an existing crack occurred, the overlays on both sides of the beam flange were sufficient to accommodate the severe axial and flexural stresses and strains. Also, the overlays at the bottom flange appeared to influence the web cope crack to propagate along the K line and not through the flange. Specimen 2, strengthened with a doubler plate at the panel zone, displayed substantial local buckling of the flanges and web. Yet the original welds, strengthened with overlays on both sides of the flanges, sustained the severe axial force and bending at the joints with the primary fracture occurring at the top flange well away from the overlays. Again, both at the top and bottom flange, the overlays appeared to influence the web cope crack to propagate along the K line and not through the flange.

Repair of minor cracks, by the conventional method, may be less expensive than Class C. The conventional repair of minor cracks involves removal of the root crack, filling the gouged area with weld and applying a fillet weld. However, the Class C overlay has the benefit of improving the performance of the weld significantly. It should also be mentioned that there have been many instances (Maranian, 1997) where excavation of minor cracks during conventional repair led to propagation of cracks through column flanges leading to more substantial repairs and costs. As a result, it may be prudent that, after removal of the backing bar by air arc gouging, grinding be used to remove small defects rather than air arc gouging. The objective of pending work is to eliminate gouging entirely.

CONCLUSIONS

Based upon both the full scale and small component tests conducted as part of this limited research program, the following procedures are recommended as methods of repair.

Minor Indications in Beam Flange Weld

Type W1a per SAC (1995), if determined that it requires repairing, may be repaired using Class C or Class C1. From interpretation of the test data (e.g the large scale test on specimen 1, where failure occurred at the top flange with only a single overlay applied), Class C or C1 will perform significantly better than the conventional repair of minor cracks. It is recommended not to plug weld the access hole as was carried out in one of the full size tests, but to enlarge the access hole thus permitting continuous application of the weld overlay.

Major Indications in Beam Flange Weld

Type W1B and W2, per SAC (1995), may be repaired using Class A or A1 welded overlays. The conventional repair, Class B, using notch tough welds, from a previous full size test performed well but failure occurred by propagating from the web cope through the beam flange. We understand similar performance has occurred in large scale tests at other institutions (Whittaker, Gilani, and Bertero, 1997). Based upon the evidence of the tests, Class A or A1 repairs appear to provide better performance than the conventional repair Class B. As mentioned previously, the weld overlays tend to influence the web cope cracks to propagate horizontally without significantly reducing the performance of the connection. Reinforcing the conventional repair with overlays (Class B2) will obviously significantly improve its dynamic performance.

Limitation for the Use of Welded Overlays

Class A, A1, C and C1 may apply to the repair of welds with beam flange thicknesses up to 2½-in., which includes the majority of beams used in steel moment frames.

This limitation is a consensus agreement of a sub-group, based upon recent static small component tests carried out on 2-in. thick specimens reported in DLW Report No. 1473

(DLW, 1999a). Static pull tests using Class A weld overlays on both sides demonstrated that the welds have sufficient static capacity to accommodate ultimate tension force with ductile failure occurring in the parent metal well away from the welds. Static bend tests, with the Class C weld overlay on the tension side only, showed very good static capacity. The one-sided Class C overlay accommodated both shear and tension, with substantial yielding and permanent deformation before failure occurred in the parent metal adjacent to the weld. It is anticipated that, subject to further testing and research particularly into other industries, the limitation on thickness can be significantly increased. Although the tests have shown excellent results, the use of overlays has been considered as a repair method. Most of the small component testing was carried out at one in. to reduce variables and obtain a clear picture. More dynamic tests on thicker specimens are planned. It is intended that value engineering studies will be reported in a revision of DLW 1341 (Simon et al., 1998).

Buttering of Column Flanges

Consideration should be given to applying a buttering layer to the face of the column flange per Class A1, Class B1 or Class C1 particularly if there is evidence in existing buildings of lamellar tearing problems. More testing and research appears necessary on this issue.

Preheat / Postheat

Preheat was not applied to any of the small scale and full size specimens. However, until further testing is carried out, the recommendations of FEMA 267 and the City of Los Angeles' recommendation (COLA, 1997) should apply. Economies may be found following further testing.

Objectives and Accomplishments to Date

The main objectives of the DLW approach is the production of a low cost weld that meets or exceeds the ultimate service load requirements and to provide positive redundancy to overcome questionable existing welds and not fully reliable inspection procedures.

The research and testing, reported above, essentially represents the culmination of the first phase of work necessary to permit the implementation of the welded overlays as a repair method for Steel Moment Frame Buildings. Furthermore, the first phase of research and testing has led to the following accomplishments:

1. The development of an approach, using supplemental high quality welds, applied over existing damaged or defective welds, to render the welded joint capable of accommodating static and dynamic demands at full yield, with significant strain and strain rates.
2. Alternative weld details to conventional full penetration welds, capable of accommodating static and dynamic demands at full yield, with significant strains and strain rates.
3. The need for small component testing in combination with full scale tests for weld quality evaluation. Since the full size beam to column test is a static test of the assembly, not a weld test, it will only give an indication of the static weld properties above a certain strength level, it must be supplemented by a small component test.
4. The use of quality weld overlays to arrest cracks.

The benefits of adopting welded overlays clearly extend well beyond repairs of steel moment frames. Subject to further research and testing, their application may prove to be suitable for modification and new construction provided that all other aspects on parent metal issues are addressed. Further economies may also be found from additional testing. Also, overlays may be shown to apply to other applications and industries (e.g. bridges, offshore structures, etc.)

A continuing research and testing effort is needed to accomplish these goals. The immediate objectives are: (a) develop the method to also apply as a retrofit for small to large sized members based upon additional small component and large scale tests. That is, the method will consistently satisfy the optimum dynamic requirements and SAC (1995) and SAC (1997) guidelines; (b) investigate refinement of weld overlay profiles and alternative overlay weld metals.

ACKNOWLEDGMENTS

(DLW, 1999b)

The authors wish to acknowledge the DLW Task Group which is a continuation of groups from other industries responsible for totally dependable weldments, e.g. the B-1 supersonic aircraft, the space shuttle booster, the S-56 helicopter engine mount and many other jet engine components redesigned from investment castings to weldments to withstand severe dynamic load conditions. The contributions of pioneers in fracture mechanics, e.g. the late Keith Lampson, is gratefully acknowledged. Space does not permit mentioning current contributors here, their specific tasks in relation to the Northridge catastrophe and outstanding issues. It is intended that this will be reported in a revision of DLW Report 1341 (DLW, 1998) describing many assembly failures that could have been prevented by a low cost DLW overlay. This was not brought out in this paper which is concentrating on the engineering aspects. The revision of DLW Report 1341 is intended to also deal with reducing potential failures of many steel structures. Readers interested, please contact Sitech Ltd., P.O. Box 3532, Winnetka, CA 91396-3532, telephone no. (818) 888-3741, fax no. (818) 888-2503.

The accomplishments of this project are directly attributable to the efforts of volunteers who donated their collective efforts and time to make the accomplishments possible.

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DEFINITIONS AND ABBREVIATIONS

Cleavage Fracture=Transgranular fracture by which fracture occurs along crystallographic planes.

DLW = Dynamic Load Weld

DWT = Drop Weight Test

Dynamic Joint Efficiency = Ratio of Weld Strength to Parent Metal Strength under Dynamic Load. Specify Testing Method, e.g. Charpy Impact, Drop Weight, LCF

FCAW-ss = Flux Core Arc Weld Self-Shielded

GTAW = Gas Tungsten Arc Welding

HAZ = Heat Affected Zone

ksi = Thousand Pounds per Square Inch.

Lamellar Tearing = Form of stepped like cracking that occurs in the base metal of a weldment due to the combination of high localized stress and low ductility of the plate in the through thickness direction.

LCF = Low Cycle Fatigue

NDT = Non-destructive Testing

PAW = Plasma Arc Welding

PPM = Parts Per Million

Redundancy, positive = Duplicate system, back-up

Redundancy, negative = Excess, unnecessary, expendable

SMAW = Shielded Metal Arc Welding

Static Joint Efficiency = Ratio of Weld Metal Strength to Parent Metal Strength Under Static Tension.

Value Engineering = The determination of relationship between engineering and cost factors.