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Autor: Caramelli, Stefano / Croce, Pietro / Froli, Maurizio

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Repair Techniques for the Rehabilitation of Fatigue Cracked Orthotropic Steel Bridges

Stefano CARAMELLI
Associate Professor
University of Pisa
Pisa, Italy

Stefano Caramelli, born in 1945, received his Civil Engineering Degree from the University of Pisa. He is currently Associate Professor of Structural Design at the Department of Structural Engineering of University of Pisa.

Pietro CROCE
Assistant Professor
University of Pisa
Pisa, Italy

Pietro Croce, born in 1957, got his PhD degree in 1989. He is Assistant Professor at the Department of Structural Engineering of University of Pisa. He is involved in several researches on bridges, fatigue and reliability.

Maurizio FROLI
Assistant Professor
University of Pisa
Pisa, Italy

Maurizio Froli, born in 1954, received his Civil Engineering Degree from the University of Pisa where he now teaches Theory of Structures.

Luca SANPAOLESI
Professor
University of Pisa
Pisa, Italy

Luca Sanpaolesi, born in 1927, graduated in Civil Engineering at the University of Pisa. He is Director of the Department of Structural Engineering of the University of Pisa. He is involved in the studies of Eurocodes.

Summary

Fatigue cracks in steel bridges can be prevented by a correct design of the details and by improving execution techniques. The results obtained in the latest research works allow to reduce significantly the risk of occurrence of fatigue cracks in new bridges, but the problem is still open in existing bridges, for which it is necessary to develop suitable repair techniques. In the paper two repair techniques for stiffener to stiffener joints are illustrated and their fatigue behaviour is widely discussed, drawing some relevant conclusion.

1. Introduction

The results obtained in the latest research works concerning the fatigue resistance of orthotropic steel deck bridges [1], [2], [3] allow to improve considerably the fatigue classification as well as the execution techniques of the welded details of this kind of structures.

Of course, the benefits obtained applying the new knowledge are particularly relevant in the design of new bridges, while in existing bridges and also in badly designed new bridges the probability of fatigue crack occurrence in the welded details remains still high. For these reasons, in the last years many research efforts have been devoted to the development of suitable repair techniques for fatigue cracked joints [4].

Being intended to be applied in existing bridges, repair techniques must fulfil some preliminary requirements, in order to minimise the time and the cost required for their execution. On the basis of the aforesaid considerations, a good repair technique should be as simple as possible, avoiding or reducing the traffic flow limitations during the works and assuring a significant residual fatigue life of the repaired details.

In the perspective of the cost reduction and of the maximum efficiency of the repair operation, it is obvious that repairs cannot be limited only to the cracked joints: in fact, to lengthen profitably the time interval between two subsequent repair plans, when fatigue cracks are detected, it is necessary to foresee a complete set of reparations, concerning cracked details as well as similar connections which are fatigue damaged even if not yet cracked.

In the present paper two repair techniques for fatigue cracked stiffener to stiffener welded joints are illustrated and their fatigue resistance, determined by testing real scale specimens, is widely discussed, with particular attention to the comparison between the residual fatigue life of cracked and repaired joints and the fatigue life of the virgin ones.

2. Preliminary results

In the framework of the studies carried out on the virgin connections, the Authors [1], [2] have investigated two types of stiffener to stiffener welded connections, indicated as type I and type II joint in figure 1.

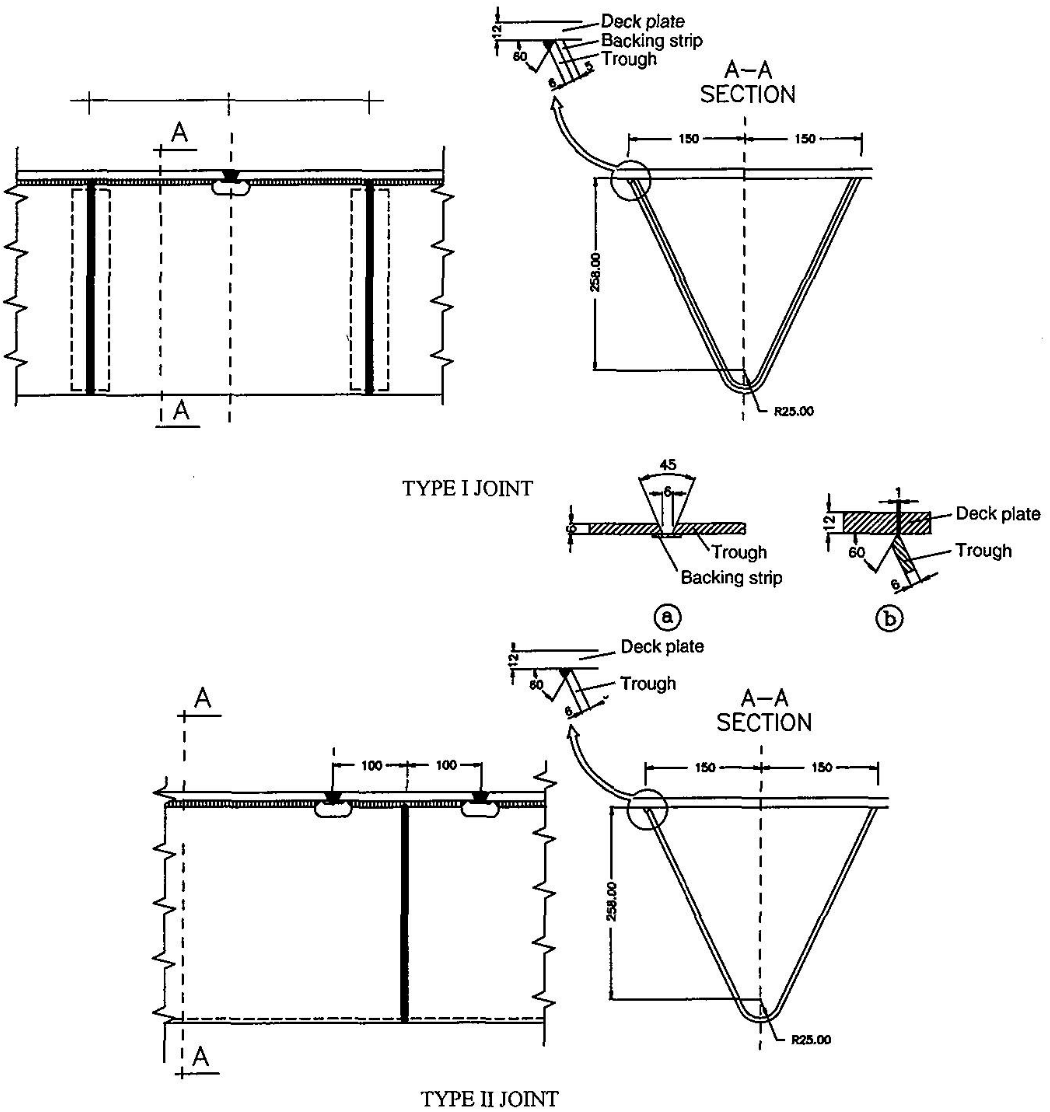


Fig. 1 Stiffener to stiffener connections

The results of constant amplitude fatigue tests, carried out on real scale specimens on a three points bending scheme, are reported in table I and plotted in the S-N diagram of fig.2, in which are reported also the characteristic S-N curves for class 71 and class 80 details of EC3 and the mean S-N curves obtained on tensile specimens with butt welds on backing strip (I* curve) and full penetration welds (II* curve).

Test n.	Connection type	σ_{max} [N/mm²]	σ_{min} [N/mm²]	$\Delta\sigma_{max}$ [N/mm²]	Number of cycles	Remarks
1	I	210	15	195	1390000	-
2	I	240	15	225	539000	-
3	II	240	15	225	251000	-
4	II	210	15	195	939000	-
5	II	190	15	175	821000	-
6	II	190	15	175	459500	-
7	I	240	15	225	468000	-
8	II	155	15	140	6040000	-
9	I	190	15	175	8100000	no crack
10	II	210	15	195	885000	-
11	I	210	15	195	1200000	-
12	I	240	15	225	896000	-
13	II	240	15	225	309000	-
14	II	190	15	175	1930000	-
15	I	210	15	195	1667000	-
16	II	140	15	125	7073000	-
17	I	210	15	195	1622000	-

***Table 1** Fatigue results on stiffener to stiffener real scale virgin joints.*

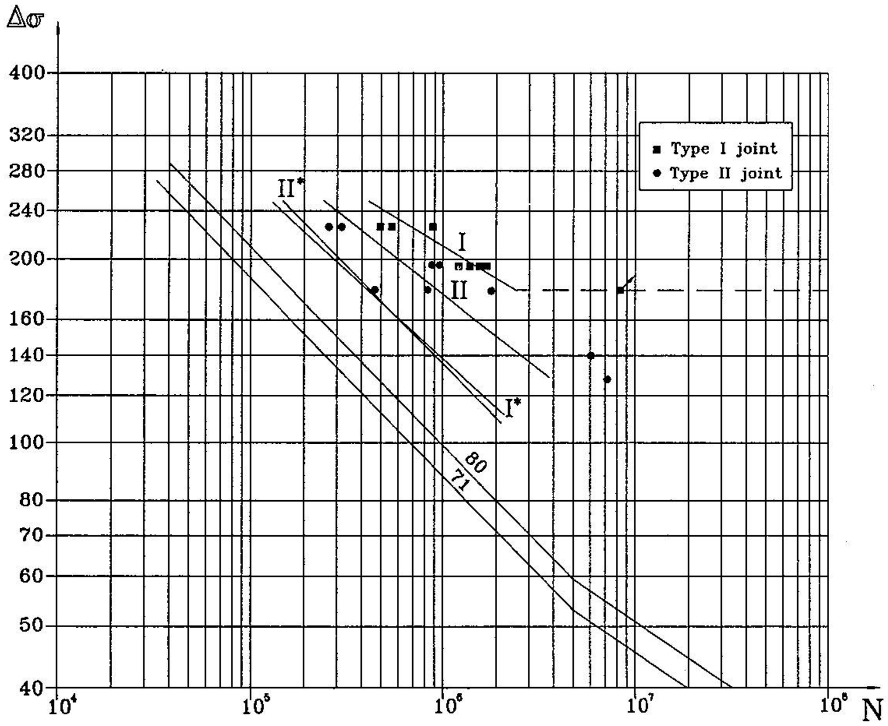


***Fig. 2** Fatigue test results on stiffener to stiffener connections*

3. Repair techniques

Regarding the stiffener to stiffener joints, two different repair techniques, described in detail in the following, have been investigated: the first one, indicated as R1, has been proposed for the rehabilitation of steel bridges in New Zealand [5] and consists in the complete replacement of the cracked joint, while an alternative technique, developed by the Authors and named R2, foresees the use of cover plates.

3.1. R1 repair

The R1 repair of fatigue cracks in stiffener to stiffener connections can be applied to different joint types and requires the following operating sequence leading to a type I joint (fig. 3):

1) Detection of the damaged joints to be repaired.
2) Flame cutting of the damaged part of the stiffener.
3) Preparation of the welding surfaces (according to fig. 3).
4) Backing strips insertion.
5) Fitting of the new stiffener elements and completion, in overhead position, of the welds between the stiffeners and between the stiffeners and the deck plate. (The welders must satisfy the requirements of AWS welder qualification tests for overhead position).
6) Visual, liquid-penetrating and magnetic-particle inspections of the welds and, if necessary, their repair.

3.2. R2 repair

The R2 repair of fatigue cracks, which is especially conceived for strengthening of type I stiffener to stiffener connections (see fig. 1), can be carried out according the following sequence, in such a way that the final geometry shown in fig. 4 is obtained:

1. Determination by means of visual, liquid-penetrating and magnetic-particle inspections of extension and location of the fatigue cracks in the whole joint.
2. Crack milling of the fatigue cracked welds: for the part of the crack located over the backing strip the minimum width of the milling must be equal to 6 mm, namely equal to the former root gap, with a depth of the 6 mm, in order to reach the backing strip (fig. 4); for the part of the crack located out of the backing strip, on the contrary, the result of the milling operation should be an U-groove edge preparation, 6 mm wide and 5 mm deep (fig. 4).
3. Milling of the apex of the fatigue damaged but not yet cracked welds: the minimum width of the milling must be equal to 6 mm, while its depth must be equal to 6 mm in order to reach the backing strip and.
4. Material cleaning and inspection.
5. Execution of the welds in overhead position. (The welders must satisfy the requirements of AWS welder qualification tests for overhead position).
6. Weld grinding in order to set to zero the over-thickness.
7. Visual, liquid-penetrating and magnetic-particle inspections of the welds and, if necessary, their repair.
8. Preparation of the cover plates, 6 mm thick: in the specific case, the dimensions of the cover plate were 1400x185 mm, with a radius of the curved edges equal to 92.5 mm.
9. Execution of fillet welds between the cover plates and the webs of the stiffener. The fillet welds, having a side size of 6 mm, run continuously around the cover plate.
10. Grinding of the fillet welds of the curved edges.
11. Visual, liquid-penetrating and magnetic-particle inspections of fillet welds and, if necessary, their repairs.

When repair concerns fatigue damaged but no-cracked joints, step 2 does not apply.

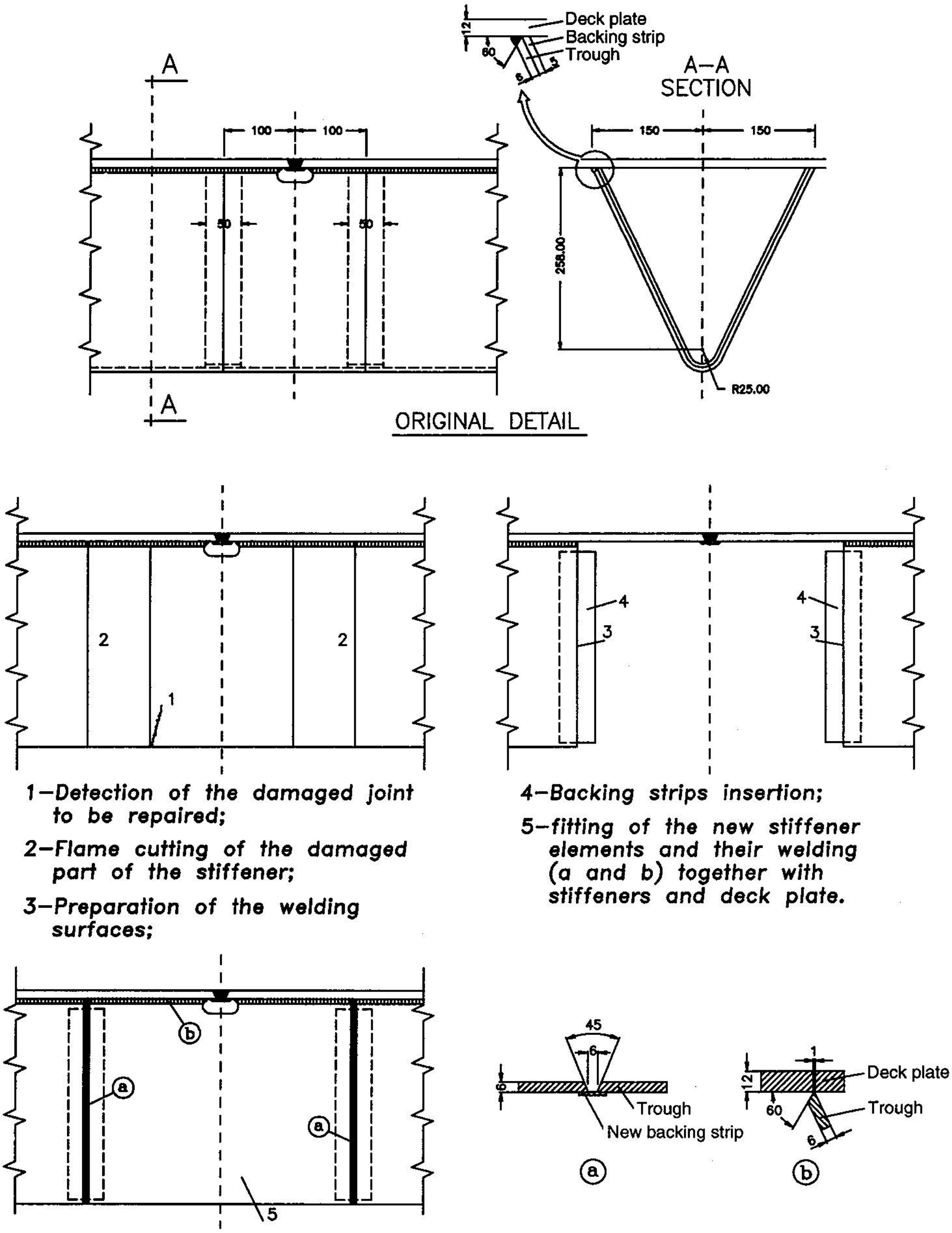
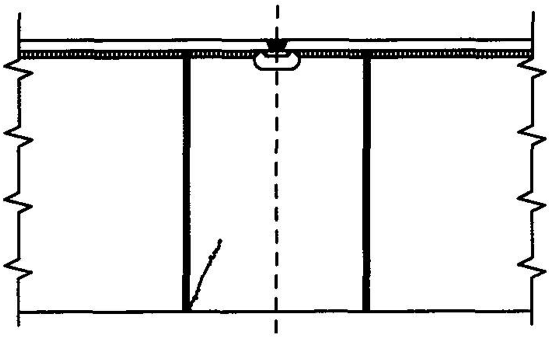
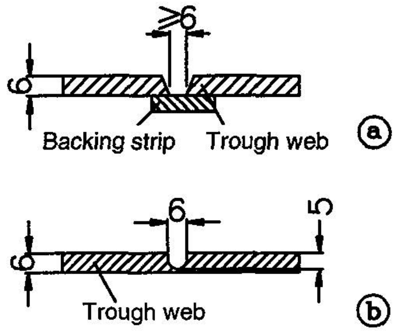


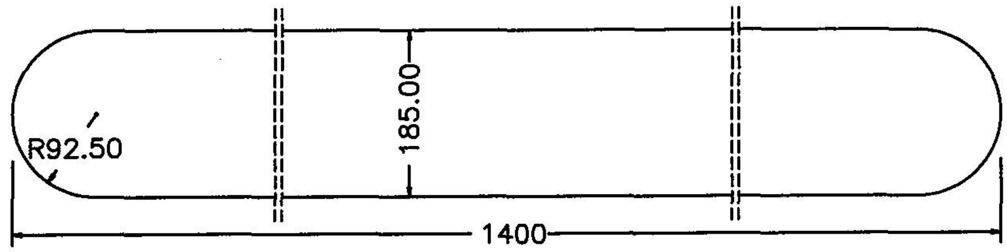
Fig. 3 R1 repair

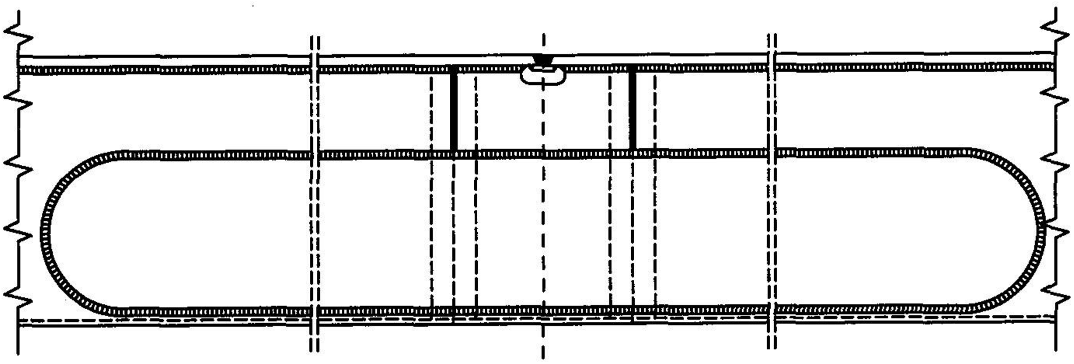




1- Determination of crack extension and location in the whole joint by means of visual, liquid penetrating and magnetic particle inspections.
2- Crack milling. For the part of the crack located over the backing strip the depth of the milling must be equal to 6 mm in order to reach the backing strip; the minimum width must be equal to 6 mm, namely equal to the former root gap (a), while for the part of the crack located out of the backing strip the milling will be carried out in order to obtain an U-groove edge preparation, 6 mm wide and 5 mm deep (b).
3- Milling of the apex of the no-cracked welds.
4- Cleaning and inspections of the material.
5- Executions of the weldings in overhead position. The weldors must satisfy the requirements of the AWS weldor qualification tests for overhead position.
6- Welds grinding to set the over thickness to zero.
7- Visual, liquid penetrating and magnetic-particle inspections of the welds and, if necessary, execution of the repair.
8- Preparation of the coverplates, 6 mm thick. The radius of the curved edges is equal to 92.5 cm while the coverplate dimensions are 1400x185 mm

Trough web





9- Fillet welding of the coverplates to the webs of the stiffener: the fillet side is equal to 6 mm. The fillet runs continuosly around the coverplate.
10- Fillet weld grinding of the curved edges.
11- Visual, liquid penetrating and magnetic-particle inspections of fillet welds and, if necessary, execution of new repairs.

The R2 repair of fatigue damaged but not cracked joints should be performed according the instructions of points 3 to 11.

Fig. 4 R2 repair

3.3. Main features of repair techniques

On basis of the operating sequences described before, it is possible to put in evidence the main features of each repair technique.

In principle, the R1 repair, which seems to be able to restore the original fatigue strength of the joint, can be used for every joint type. It can be applied upon all damaged joints even if not cracked, but during the work it is necessary to deviate the traffic so that the repair operations must be limited, time to time, to small deck areas, increasing the repairing time. Further disadvantages of this technique are related to the difficult fitting of the new stiffener elements to the existing ones and to the possible reduction of the fatigue strength of the deck plate to stiffener joint.

The R2 repair can also be carried out both on cracked and uncracked joints but it seems, at first sight, unable to restore the original fatigue strength of the joint, because the damaged areas are not completely removed. Nevertheless it must be noted that, locally, the section modulus of the stiffener becomes higher, due to the effect of the cover plates, so that the stress level in the weld, at the apex of the stiffener, is considerably reduced. On the base of these considerations, the additional fatigue life could be relevant. Besides, the R2 repair appears easier, cheaper and quicker in execution than the R1 repair, even if its application is limited to type I joints.

4. Fatigue tests on repaired specimens

In order to evaluate the additional fatigue life of the repaired connections, to be compared with the fatigue life of virgin ones and with the expected residual life of the orthotropic deck, test specimens in real scale have been prepared, reproducing the effective field situation, using the fatigue cracked specimens obtained from the previous research [1], [2]: taking into account the peculiarities of each type of repair, type I joints have been repaired using the R2 technique, while type II joints have been repaired using the R1 technique.

Constant amplitude fatigue tests on repaired stiffener to stiffener connections have been carried out on a three points bending scheme, with the pulsating load on the joint axis, located at the mid-span of the stiffener (Figure 5).

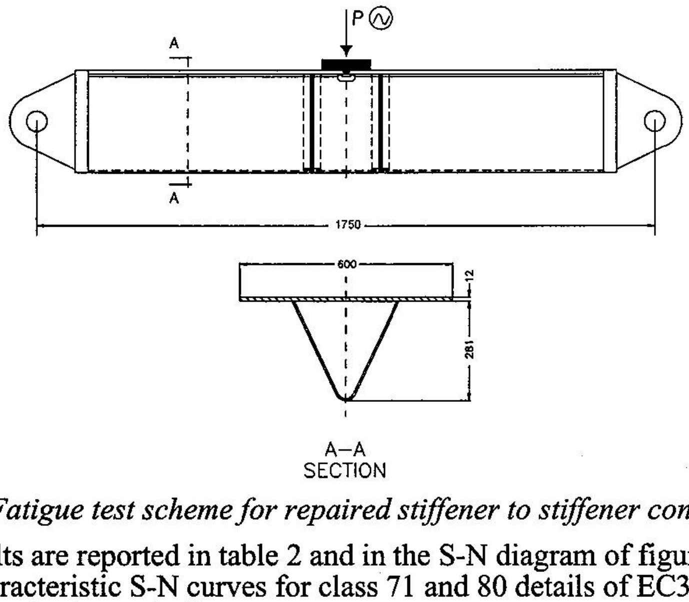


Fig. 5 Fatigue test scheme for repaired stiffener to stiffener connections

The fatigue test results are reported in table 2 and in the S-N diagram of figure 6, in which are also reported the characteristic S-N curves for class 71 and 80 details of EC3 and the relevant mean S-N curves already shown in fig. 1.

The test results on R2 repairs are reported in terms of nominal stresses, both taking into account the section modulus increase due to the presence of the cover plates (these stresses are indicated as *actual stresses)* or not, i.e. considering the stresses which should be obtained in the original cross section, disregarding the presence of the cover plates themselves. Obviously, for R1 repaired specimens are considered only nominal stresses.

N.	Type of repair	σ_{actmin} [N/mm²]	σ_{actmax} [N/mm²]	$\Delta\sigma_{actual}$ [N/mm²]	$\Delta\sigma_{nominal}$ [N/mm²]	Number of cycles
1	R2	15	180	165	250	250 000
2	R1	15	240	225	225	875 000
3	R1	15	240	225	225	750 000
4	R2	15	151	136	200	1 650 000
5	R2	15	89	74	109	2 560 000
6	R1	15	240	225	225	700 000
7	R2	15	166	151	230	2 850 000
8	R1	15	240	225	225	60 000
9	R1	15	185	170	170	190 000
10	R2	15	166	151	230	450 000
11	R1	15	185	170	170	310 000
12	R1	15	130	115	115	750 000
13	R1	15	130	115	115	1 200 000

***Table 2** Test results on stiffener to stiffener repaired joints*

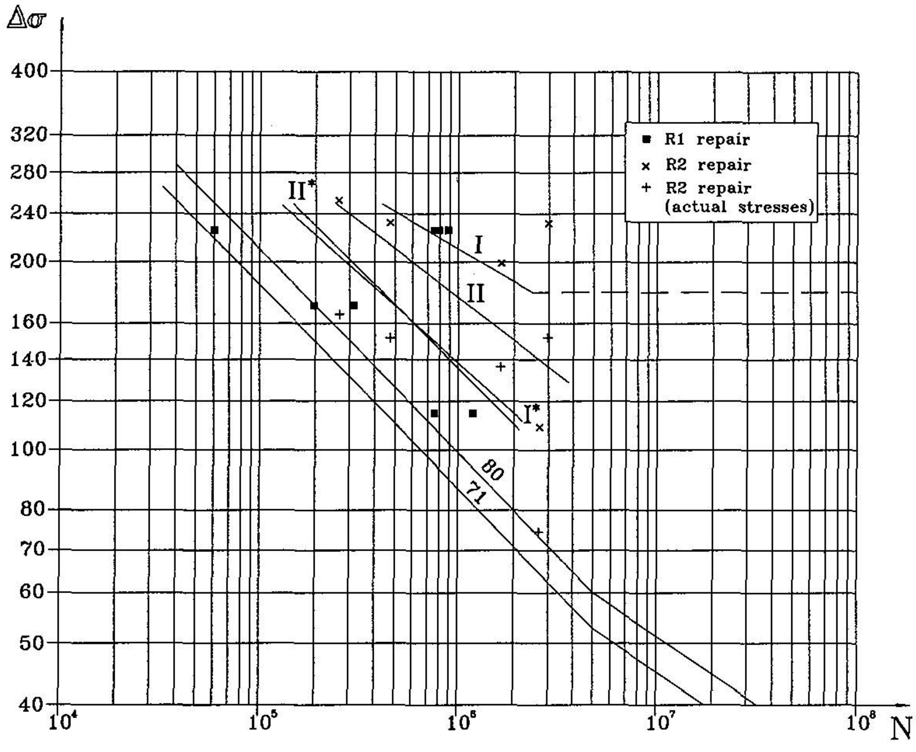


***Fig. 6** Fatigue test results on repaired stiffener to stiffener connections*

Concerning the failure mode, it has been observed that in R1 repaired specimens cracks start always at the apex of the stiffener, in the weld, propagating in the weld itself; while in R2 repaired specimens n.1 and n. 10 cracks start at the apex of the stiffener, in the weld, propagating through the cover plates, and in R2 specimens n. 4, n. 5 and n. 6 the cracks start at the apex of the stiffener in correspondence of the tack weld of the baking strip, propagating through the cover plates.

The test results show that :

- the fatigue strength is more scattered for repaired joints than for virgin ones;
- all test results are above the characteristic S-N curve for class EC3 71 detail;
- the original fatigue life is not completely restored with R1 repair;
- R2 repair gives, in terms of actual stresses, the same residual fatigue life as R1 repair;
- in terms of nominal stresses, i.e. with the same traffic loads, R2 repair gives a residual life appreciably higher than that assured by R1 repair and comparable with the fatigue life of type II virgin joints;
- R1 repair can be classified as 71;
- R2 repair can be classified as 71, in terms of actual stress;
- R2 repair can be classified as 100, in terms of nominal stress.

5. Conclusions

The fatigue tests carried out on repaired specimens lead to the following relevant conclusions about the two repair techniques, which have been proposed for stiffener to stiffener joints, even in view of design recommendations :

1) both techniques can be easily performed;

2) fatigue behaviour of the R2 repair is not significantly influenced by the welding of the cover plate;

3) the original fatigue life is not completely restored with R1 repair;

4) R2 repair gives a residual life appreciably higher than that assured by R1 repair and comparable with the fatigue life of type II virgin joints;

5) R1 repair can be classified as 71;

6) R2 repair can be classified as 100, in terms of nominal stress;

7) R2 repair technique almost restores the fatigue life of the joint and it represents a good compromise between costs and benefits, so that it results suitable for practical applications.

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