13

Practical and Economic Aspects of Application of Austenitic Stainless Steel, AISI 316, as Reinforcement in Concrete

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ABSTRACT

Reinforced concrete used for housing and industrial construction is often damaged due to corrosion of the reinforcement. The total cost in the EC for repair of damages caused by corrosion may be estimated from the cost in the UK on highways alone to be around 50M ECU per year.

A way to lengthen the lifetime of a structure is to use corrosion resistant reinforcing materials, e.g. stainless steel. The intelligent use of stainless steel, which means combining with traditional carbon steel in locations exposed to very corrosive environments, can be a very cost-effective option when considering different rehabilitation methods.

However, most civil engineers have an unfounded fear of using stainless steel and carbon steel together in the same concrete structure. For this reason, the behaviour of the austenitic stainless steel, AISI 316, in connection with carbon steel has been evaluated in order to study the consequences of galvanic coupling for corrosion reinforced concrete structures. The experimental study includes results from different concrete samples, in which AISI 316, stainless steel, has been combined with carbon steel in the proportions that are foreseen for on-site applications. These results include measurements of the macrocouple current between stainless steel and carbon steel during exposure to accelerated ingress of chloride. Additionally, measurements of electrochemical potentials and corrosion rate of the macrocouple were made.

The obtained results show that galvanic coupling with stainless steel results in an enhanced corrosion rate of the active carbon steel in a chloride-contaminated solution. A Life Cycle Cost calculation, based on practical cases of repaired bridge columns, has confirmed that the intelligent use of stainless steel in combination with carbon steel is very cost-effective.

1. Introduction

Stainless steel derives its corrosion resistance from a naturally occurring chromium-rich oxide film that is present on its surface. This invisible film is inert, tightly adherent to the metal, and — most importantly — in an environment where oxygen is present even at relatively low levels, the film reforms instantly if the surface is damaged [1]. There are, however, aggressive environments (e.g. those with carbonation or ingress of chlorides) that can give rise to breakdown of this passive layer, resulting in corrosion of the unprotected surface. When deterioration has developed to a given point, rehabilitation measures are required. Among the various rehabilitation options, modern stainless steel has become an attractive alternative compared to traditional methods with carbon (unalloyed) steel, epoxy coatings, corrosion inhibitors, cathodic protection, etc. [2].

Stainless steel is becoming cheaper, although still 5–8 times more expensive than uncoated carbon steel.

Therefore, an economical and technically attractive approach may be to substitute carbon steel with stainless steel in critical areas, such as the lower section of a column on a highway bridge exposed to de-icing salt, the splash zone for coastal structures, or an edge beam on a highway bridge. This is called 'intelligent use' (Fig. 1).

2. Practical Aspects

The manageability of stainless steel on-site is comparable to normal carbon steel. Therefore, no special precautions need to be taken when using stainless steel. However, due to the high cold-working properties of stainless steel, somewhat higher bending forces are necessary. For repairs comprising selective replacement of carbon steel with stainless steel in a limited area, three methods can be used to connect the stainless steel and carbon steel reinforcement: traditional unwelded laps, welded laps and mechanical couplers.

The diameter of the main reinforcement is typically in the range of 15 to 40 mm, requiring a minimum grip length (~ lap length) of more than 50 cm at both ends. Therefore, unwelded lap joints are not a very competitive option, since an additional 1–1.5 m of concrete is to be removed.

Stainless steel bars are weldable on-site, whereas the weldability of the existing carbon steel bars is often questionable — and in some cases unknown. Therefore, welding on-site may not always be possible.

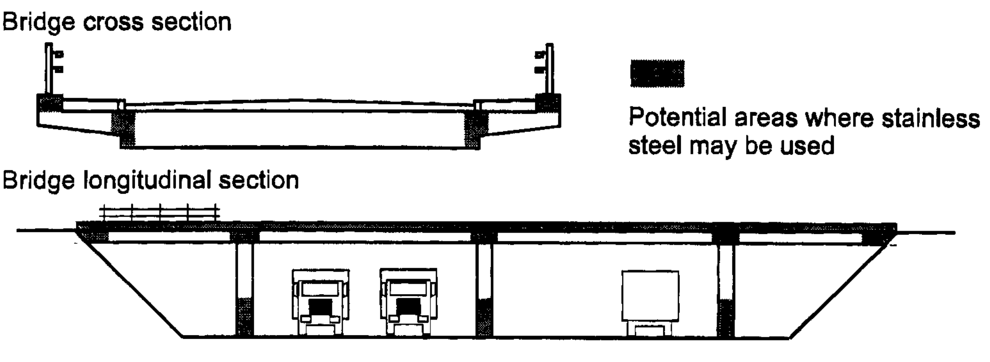

Fig. 1 Potential areas where stainless steel may be used intelligently for repair and in new structures as well.

The corrosion resistance of stainless steel is lowered by welding and by contamination with iron deposits from tools used in the handling [3]. However, problems may be avoided by careful post-treatment, e.g. sandblasting and pickling.

The use of mechanical stainless steel couplers between carbon steel bars and the stainless steel reinforcement is an alternative to welding. Some of these require that a thread be made on the existing carbon steel, which may be both difficult and time-consuming on-site. Another option is to use couplers that mechanically lock the bars to the coupler, thereby achieving strengths higher than the yield strength of the rebar itself. By using mechanical steel couplers, no additional lap length is required. The mechanical couplers can be made from stainless steel. The example in this paper assumes the use of the mechanical couplers described above.

3. Corrosion Aspects

Stainless steel that is freely exposed to sea water may, if in galvanic contact with a less noble metal such as carbon steel, initiate a galvanic type of corrosion of the latter. The corrosion rate will depend on the area ratio between the carbon steel and the stainless steel. The otherwise slow, cathodic oxygen reduction at the stainless steel surface is a catalyst for bacterial slime, which forms after a few weeks in sea water.

When stainless steel is cast into concrete, however, the cathodic reaction is a very slow process, since no such catalytic activity takes place on a stainless steel surface [4]. A research project conducted at the FORCE Institute [5] has indicated that the cathodic reaction is inhibited on stainless steel embedded in concrete, as compared to the cathodic reaction on carbon steel reinforcement in galvanic contact with corroding carbon steel.

Later publications by Pedeferri *et al.* [6] and Jaggi *et al.* [7] also provide results which confirmed the above findings.

Consequently, the connection between stainless steel and carbon steel should not promote significant galvanic corrosion. As long as both metals are in the passive condition, their potentials will be more or less the same when embedded in concrete. Even if there should be minor differences in potential, both carbon and stainless steel can be polarised significantly without any serious risk of corrosion, as their potentials will approach a common value without passage of significant current. Therefore, assuming the correct use of stainless steel, the two metals can be coupled without any problem in all positions where chloride ingress and subsequent corrosion might occur.

This behaviour, and the fact that stainless steel is a far less effective cathode in concrete than carbon steel, makes stainless steel a useful reinforcement material for application in repair projects. When part of the corroded reinforcement, e.g. close to the concrete cover, is to be replaced, it could be advantageous to use stainless steel instead of carbon steel. Since it is a poor cathode, the stainless steel should minimise any possible problems that may occur in neighbouring corroding and passive areas after repair.

At the same time, it is very important for the intelligent use of stainless steel that it be combined with carbon steel in proportions that guarantee both an optimal performance and cost-effective solution. For this reason, tests including probable volume combinations of between stainless steel and carbon steel aimed for repair of damaged highway and coastal bridges have been carried out.

4. Experimental Tests of Corrosion Resistance

The aim of the experiments described in this paper is to define objectives for use of stainless steel in the repair of corroding reinforcement. The galvanic couple formed between the passive stainless steel and the existing carbon steel, which in some cases is passive and in some cases corroding, will be studied in order to prove that the use of stainless steel for this purpose might even have a beneficial effect.

All test samples have the dimensions 300 × 170 × 70 mm and are cast from an ordinary Portland cement concrete of water/cement (w/c) ratio = 0.5 and without addition of fly ash and microsilica. All samples contain 5 reinforcement bar pieces in full sample length. These bars are either made of carbon steel or austenitic stainless steel (AISI 316). Additionally, the test samples contain two small pieces of the austenitic stainless steel or carbon steel, corresponding to 5–10% of the total steel volume. The 5% and 10% chosen for the samples represent the percentage of stainless steel foreseen for use in application on-site. All bars have a diameter of 6 mm. A reference electrode of the MnO_2 type is embedded in each sample. A total of 10 concrete samples divided into four groups was cast and later used for measurements of galvanic current, electrochemical potentials and corrosion rate.

Figures 2 and 3 show the samples and the principles of measurement.

One month after casting, all samples were exposed in a concentrated solution of NaCl (165 gL^{-1} NaCl) with addition of $Ca(OH)_2$. In order to accelerate the chloride ingress, the exposure was a cycle of two days wetting in the NaCI solution and five days drying in a laboratory atmosphere [8]. The following measurements were conducted:

- Macrocouple current between stainless steel connected to carbon steel. The macrocouple current is measured by means of a specially constructed Zero Ohm Ammeter.
- Electrochemical potential of the abovementioned macrocouple against an embedded MnO_2 reference electrode.
- Corrosion rate of all rebars by means of a galvanostatic pulse method.

5. Results of Corrosion Experiments

5.1. Macrocouple Current

The rapid potential drop in the corroding metal causes a significant increase in macrocouple current when the corrosion process starts. Thus, an electromotive force between two metals with different electrochemical potentials is created, resulting in

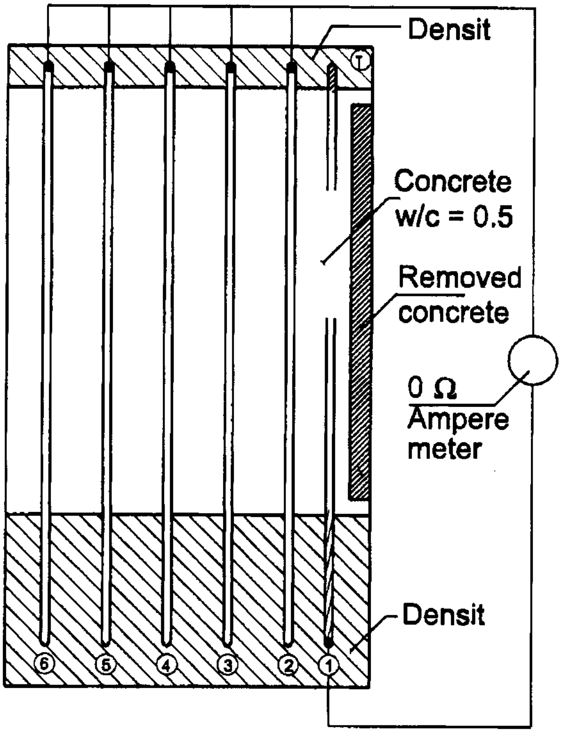

Fig. 2 Sketch of test samples.

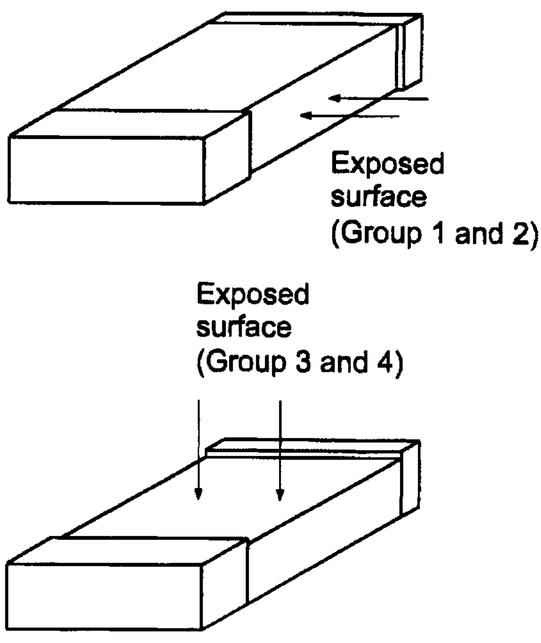

Fig. 3 Principle of exposure of test samples.

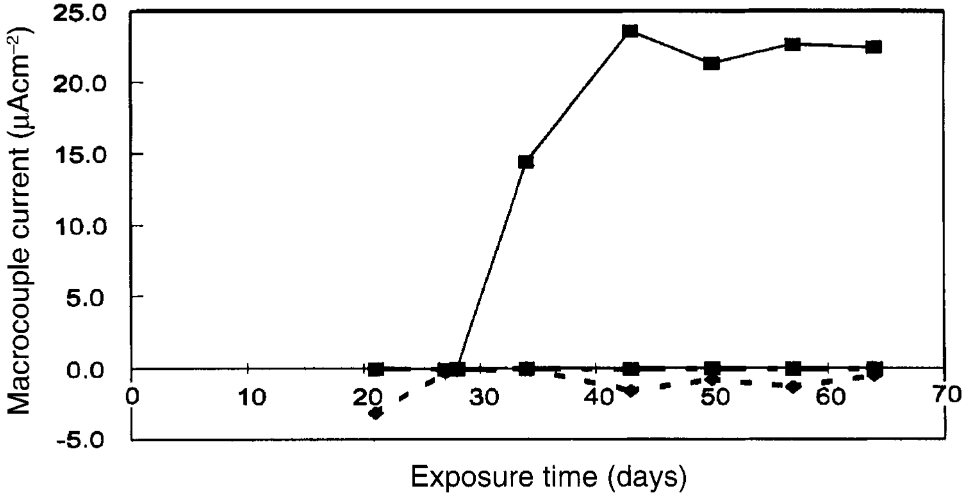

Fig. 4 Macrocouple current as function of exposure time.

the electrical current (corrosion current) flowing between them. Figure 4 shows an example of macrocouple current measurements made on one of the test samples represented in group 3. This sample had been cast from ordinary Portland cement with w/c ratio = 0.5 and without addition of fly ash and microsilica. Austenitic stainless steel, AISI 316, represents 10% of the total steel volume in the sample. During the exposure and measurements of the macrocouple current stainless steel was electrically connected to the carbon steel. At the beginning of the experiment the measured current was very low due to passivity of both stainless steel and carbon steel. After 28 days of exposure in the concentrated NaCl solution this current rapidly increased due to pitting corrosion occurring on the carbon steel.

The increase in macrocouple current after initiation of corrosion depends on the type of passive material (cathode). The current will be much lower when corroding carbon steel is connected to a passive stainless steel, compared to the current registered between active and passive bars of carbon steel. For this reason, the increase in corrosion rate in carbon steel due to the galvanic coupling with stainless steel will be significantly lower than in the case of carbon steel.

The experimental results from measurements performed on sample 3 representing group 1 (Fig. 5) confirm this behaviour. When the current was measured between the carbon steel rebar starting to corrode and a small rebar (5%) of carbon steel that was still passive, a current density value of approx. 4.3 μAcm^{-2} was registered. If the same corroding carbon steel rebar was connected to the small rebar (5%) of stainless steel, the measured current density value was reduced to only 0.27 μAcm^{-2}. This means a reduction in current density by a factor of approximately 15, which will result in a smaller decrease in corrosion rate.

The above numbers are typical of values measured on the remaining 9 samples included in these experiments.

The high cathodic overvoltage on stainless steel means that when stainless steel is polarised to a negative potential as a result of galvanic coupling with corroding carbon steel, it can produce a current density several times lower than the passive carbon

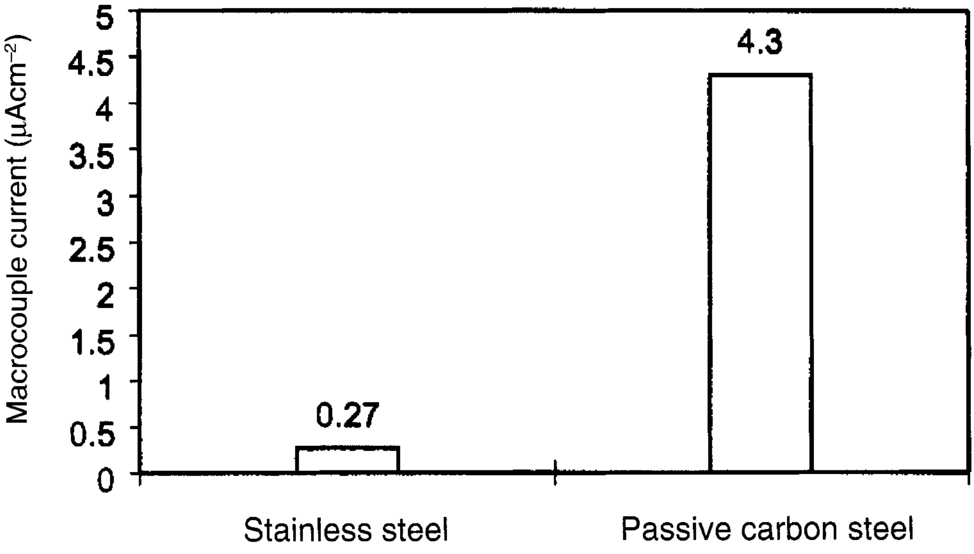

***Fig. 5** Macrocouple current for stainless steel and passive carbon steel.*

steel can generate [9]. Thus, the consequence of coupling with stainless steel is generally negligible, since passive areas of carbon steel always surround the area where corrosion takes place.

This behaviour has been proved in the present investigations. In one of the samples with small bars of stainless steel (sample No. 5 representing group 2 where stainless steel represents 5% of the total steel volume), the remaining bars of carbon steel, which had started to corrode, were coupled to the still passive small bars of carbon steel from another sample. This resulted in a remarkable increase in macrocouple current. This current started to decrease when the primary connection between carbon steel and stainless steel was re-established. The results of this test are shown in Fig. 6. This procedure has been repeated on two more samples (sample No. 1 and sample No. 7) with similar results.

As a consequence of these findings, stainless steel is considered to be an even better reinforcement material than the usual carbon steel for use in repair projects where part of the corroded reinforcement is to be replaced. Because it is a poor cathode, the stainless steel will minimise eventual problems that could occur in neighbouring corroding and passive areas after repair.

6. Determination of Corrosion Rate by Means of Galvanostatic Pulse Method

The galvanostatic pulse method is a transient polarisation technique working in the time domain. A short-time anodic current pulse is imposed galvanostatically on the reinforcement from the counter electrode placed on the concrete surface [10–12]. The applied current is usually in the range of 10 to 200 μA and the typical pulse duration

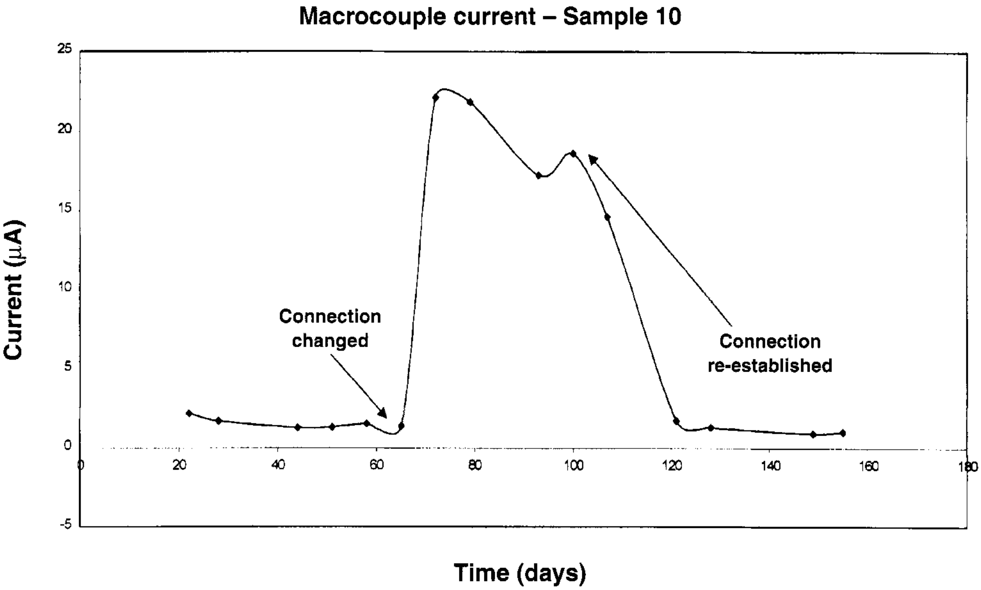

Fig. 6 *Influence of cathode material on the macrocouple current (see p.127).*

is up to 10 s. The reinforcement is polarised in the anodic direction, i.e. compared to its free corrosion potential.

The resulting change in potential is dependent on the state of corrosion in the reinforcement, and can be expressed by means of polarisation resistance, ohmic resistance, double layer capacitance and the impressed current. Thus, it is possible to calculate the polarisation resistance and, moreover, the corrosion current. When the area of polarised reinforcement is known, it is also possible to calculate the instantaneous corrosion rate from the values of the corrosion current.

In the case of the present investigation, the area of polarised reinforcement was known exactly. However, the small size of the rebar in the investigated samples caused another problem. Even the smallest current that could be applied by means of the galvanostatic pulse device was found to be too big to achieve the optimal polarisation conditions (reinforcement should only be polarised to a maximum 20 mV from the free corrosion potential when the ohmic resistance is subtracted).

Therefore, the rather high current applied for polarisation influences the obtained results. This high current has a special effect on the values of the corrosion rate determined for passive rebars (mostly stainless steel). These values are higher than could be expected for steel in the passive condition, but, nevertheless, the calculated corrosion rate values are much lower for passive stainless steel than for actively corroding carbon steel.

Experimental data from on-site measurements has shown that the average corrosion rates determined by means of the galvanostatic pulse equipment underestimates the real corrosion rate by a factor of 5–10, or even more, in the case of chloride-induced localised corrosion ('pitting'), where the active corroding area is much smaller than the confined area of the reinforcement used for the calculation.

Table 1 shows values of instantaneous corrosion rate calculated from galvanostatic

Table 1. *Average corrosion rate values calculated by means of galvanostatic pulse measurements and actual corrosion rate values obtained by correction of the corroding surface area*

Sample	Reinforcement material [1]	Free Corrosion Potential (mV vs MnO_2)	Average corrosion rate (μm/year) [2]	Actual corrosion rate (μm/year) [3]
3	1– Stainless Steel (5%)	–263	2.0	2.0
	Stainless Steel (10%)	–223	1.1	1.1
	2– Carbon Steel	–175	7.7	385
	3– Carbon Steel	–162	7.6	23
	4– Carbon Steel	–237	3.3	9.8
	5– Carbon Steel	–185	3.9	1.9
	6– Carbon Steel	–180	2.9	2.9
6	1– Carbon Steel (5%)	–575	78	233
	Carbon Steel (10%)	–553	19	75
	2– Stainless Steel	–280	1.5	1.5
	3– Stainless Steel	–278	1.4	1.4
	4– Stainless Steel	–276	1.4	1.4
	5– Stainless Steel	–270	1.6	1.6
	6– Stainless Steel	–274	1.4	1.4
9	1– Stainless Steel (5%)	–199	7.9	7.9
	Stainless Steel (10%)	–262	0.7	0.7
	2– Carbon Steel	–554	18	359
	3– Carbon Steel	–570	56	845
	4– Carbon Steel	–643	42	422
	5– Carbon Steel	–586	34	508
	6– Carbon Steel	–625	80	161

[1]Numbers before the reinforcement material indicates which bars have been galvanically connected. The bar with no number has not been connected.

[2]Values of corrosion rate calculated by means of galvanostatic pulse measurements without correction for the actually corroding surface area determined by means of the visual inspection.

[3]Values of corrosion rate after correction for the actually corroding surface area determined by means of the visual inspection.

pulse measurements without correction for the actually corroding surface area, as determined by means of the visual inspection. Based on the visual inspection the surface area of the corroding reinforcement is determined and then used for calculation of the actual corrosion rate. As expected, from experimental experience from on-site measurements, the values for the corroding carbon steel are much higher than values calculated by means of the galvanostatic pulse measurements. Laboratory experiments are therefore in good agreement with on-site measurements.

7. Total Cost and Updated Life-cycle Cost Analysis (ULCCA)

The intelligent use of stainless steel is evaluated by analysing an example of deteriorated, standard reinforced concrete (RC) columns of a coastal bridge in the splash zone.

The rehabilitation of a RC-column can be analysed separately from the rest of the bridge. This is possible as the administration, inspection, maintenance, rehabilitation, etc. are normally carried out independently of the rest of the bridge.

The two types of repair will be analysed using the net present value method, taking all costs into account (direct and indirect) from the time of repair and onwards. This updated life cycle cost analysis (ULCCA) will consider all relevant financial and technical aspects. The 'U' for 'updated' is added to 'LCCA', since the life cycle cost analysis starts when the structure is e.g. 30 or 40 years old and showing signs of serious deterioration.

The comparison of different strategies — with and without the use of stainless steel — using the net present value method is carried out in order to determine the repair strategy that is economically optimum for society as a whole, given the premises at the time of decision. This includes taking all costs into consideration; repair, maintenance, administration and indirect cost to society (traffic alterations). This is a generally accepted method approved in Denmark and several other countries [13].

8. Example of Repair of Reinforced Concrete Columns on a Coastal Bridge (Splash Zone)

An ongoing research project financed by the Danish Road Directorate shows that some fairly new coastal bridges need repair in the splash zone due to chloride-induced corrosion [14].

In this example, a 30-year-old coastal bridge with 12 columns with severe corrosion of the reinforcement in the splash zone is considered. The repair requires replacement of the outer layers of the steel reinforcement that had experienced heavy corrosion. The replacement is in the splash zone, i.e. from 0.5–1 m below to 2 m above normal sea level. The repair requires that approximately 50% of the outer layer of reinforcement be replaced in this area. The amount of steel to be replaced is approximately 5% of the total reinforcement steel in the column and foundation.

The three strategies proposed for rehabilitation of the coastal bridge are shown in Table 2 and the corresponding net present value analysis is shown on Fig. 7.

The life cycle cost analysis shows that for discount rates between 5% and 7% the three analysed strategies have comparable net present values. Based on this, it seems that a postponed repair strategy using stainless steel will be cost-optimal. It must be noted here that from experience — and the available data for the extent of deterioration and associated repair — the repair cost for coastal bridges is less than for the repair of highway bridges [15]. This is due to the higher number of repairs performed on highway bridges compared to the number of repairs performed on coastal bridges.

Table 2. Description of three repair strategies for coastal bridges

Strategy	Description of repair strategy
1	Repair of all columns using carbon steel after 1 year. The repair is done over 2.5–3 m of each column involving the breaking up of the concrete to behind the reinforcement and replacement of 50% of the reinforcement. The column in this example has two layers of reinforcement and only the outer layer is likely to corrode. At 20 and 40 years minor repair is required in the columns.
2	Repair of all columns using carbon steel after 10 years. The repair is done over 2.5–3 m of each column involving the breaking up of the concrete behind the first layer of reinforcement and replacement of 80 % of the reinforcement. At 25 and 45 years minor repair is required on the columns.
3	Repair of all columns using stainless steel after 1 year. Same repair as strategy 1, i.e. only the outer layer of old carbon steel reinforcement is replaced with stainless steel. At 20 and 40 years minor repair is required in the columns.

9. Case from Mexican Gulf — The Most Convincing Argument for Summary

The 2 100 metre long concrete pier in the Port of Progresso, Yucatan, Mexico was constructed between 1937 and 1941. The concrete pier has 175 spans of 12-m lengths and consists of massive columns and arches. Due to the harsh environmental exposure of the pier (hot and humid marine environment), it was decided to use stainless steel reinforcement (AISI 304) in selected areas of the pier.

Now, almost 60 years after construction, the pier has been investigated by means of visual inspection and both non-destructive and destructive techniques [16].

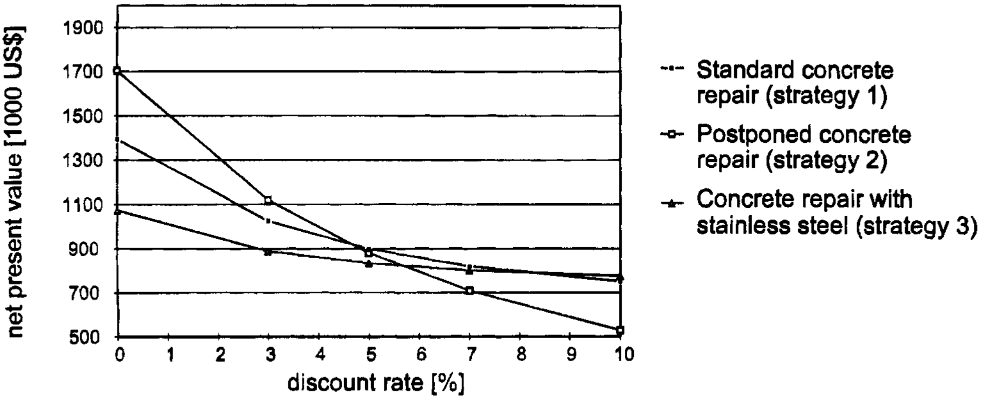

Fig. 7 Example of the coastal bridge. Net present values (50 years remaining lifetime) for different discount rates.

No serious sign of corrosion of the stainless steel reinforcement embedded in the concrete was found. However, corrosion was detected on the freely exposed reinforcement (no cover), as could be expected for this grade of stainless steel in a marine environment. For reinforcement with a cover larger than approx. 20 mm, there was no significant corrosion on the bars, despite the extremely high chloride contents of up to 1.9% Cl^- of dry concrete weight. This is at least 10 times of that normally regarded as a critical chloride concentration for the initiation of corrosion of ordinary carbon steel.

For a reinforced concrete structure in marine environment with ordinary carbon steel, the lack of routine maintenance for a 60-year period would in many cases result in serious chloride- or/and carbonation-induced corrosion problems. This is clearly shown by the deterioration of the neighbouring pier located to the west of the inspected pier.

The unambiguous conclusion is, therefore, that the use of AISI 304-grade stainless steel as reinforcement has contributed significantly to the good durability of the Progresso pier.

10. Conclusions

The following conclusions can be drawn based on the experience gained from this work:

- The coupling of corroding carbon steel with austenitic stainless steel, AISI 316, is without risk and provides lower corrosion current (corrosion rate) compared to the coupling to passive carbon steel, which always surrounds the corroding areas.

- Stainless steel has a higher overvoltage for cathodic reaction of oxygen reduction with respect to carbon steel. Therefore, the increase in corrosion rate on carbon steel embedded in chloride-contaminated concrete due to galvanic coupling with stainless steel is significantly lower than the increase brought about with passive carbon steel.

- Welding, which also decreases the chloride threshold value for initiation of corrosion, can destroy the low cathodic activity of stainless steel. For this reason the influence of welding will be further investigated in the future. The influence of cold working processes on the corrosion properties of stainless steel will also be investigated.

- However, the evidence obtained so far, shows that carbon steel and stainless steel can be coupled with beneficial results regarding corrosion protection in chloride-contaminated concrete.