Stainless Steel Reinforcing Bars in Concrete

by

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ABSTRACT

Stainless steel reinforcing bar is being used for highway bridge decks, overpasses, tunnels, retaining walls, and restoration projects where corrosive conditions could cause premature failure of carbon steel reinforced concrete resulting in potentially severe damage and high repair costs.

Stainless steel is selected for its corrosion resistance, strength and long life. The increase in installed cost using stainless steel reinforcing bar ranges from one to fifteen percent depending on structure complexity. When Life Cycle Cost and longer reinforcing bar life of up to 125 years are factored in stainless steel is very cost effective.

Emphasis will be placed on the mechanical and physical properties of stainless steel compared to carbon steel rebar as this information is important to those who wish to specify stainless steel reinforcing bar. Also some stainless rebar applications around the World will be recognized. In addition, a description of laboratory and field tests, involving U-bent stainless steel specimens embedded in concrete are noted.

Keywords: stainless steel, reinforcing bar, bridge deck, overpass, alloys, mechanical and physical properties, corrosion resistance, Life Cycle Cost

THE PROBLEM

Concrete has inherent strength and is fairly durable. However, oxygen and chloride penetrate concrete and contact the carbon steel reinforcing bar. This leads to corrosion of the steel, resulting in rust which expands, putting pressure on the concrete, producing cracks and spalling. Thus, the integrity of the structure is compromised. Figure 1 exhibits exposure of carbon steel reinforcing bar in the Gardner Expressway an elevated roadway in Toronto Canada. Some bars are completely corroded. The bars were discovered when underlying carbon steel I-beams were replaced.

To overcome the problem of corroding carbon steel, leading to concrete failure, structural problems and costly repairs, we can change the environment or change the material. With road salt seeping into concrete, there is little hope of changing this environment. Similarly, in a marine environment, salt content will not change. Instead, changing carbon steel reinforcing bars to a more corrosion resisting alloy, such as stainless steel, is a cost-saving, effective measure to extend the life of the structure. Also, the use of stainless steel offers cost savings that can be realized by eliminating rebar coatings, cement inhibitors, concrete sealers, membranes, and thicker concrete overlay, as well as financial loss due to traffic and commercial upsets.

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If the environment is also considered for multiple bridge repair there are added costs in terms of lengthened journeys, delivery delay and more fuel is burned as vehicles sit at idle. There is added cost in drilling, blasting, crushing and transport of aggregate, cement and the attendant power units to manufacture these items.[1]

BACKGROUND

Selection of stainless steel is based upon its corrosion resistance, strength, and long life.
When selected, the overall increase in project installed costs, depending on project complexity, ranges from one to fifteen percent.[2] When Life Cycle Costs (LCC) are calculated using stainless steel rebar and design life figures of up to 125 years this product becomes very cost effective as repair work becomes necessary for carbon steel reinforced structures earlier in the cycle. Many structure designers are now employing LCC in their calculations.

Standards for stainless steel rebar are in place. In the United Kingdom, The British Standard Specification is BS 6744:1986, Austenitic Stainless Steel Bars for the Reinforcement of Concrete, which lists alloys such as Types 304 (UNS S30400), 304L (S30403), 316 (S31600) and 316L S31603).[3] In the United States, the American Society for Testing and Materials (ASTM) A 955-96, Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement, contains stainless steel alloys such as austenitic Types 304 (UNS S30400), 304L (S30403), 316 (S31600), 316L (S31603), 316LN (S31653) and duplex 2205 (S31803).[4] A supporting document is ASTM A 276 Specification for Stainless and Heat-Resisting Steel Bars and Shapes.

Tests on stainless steel for reinforcing bars originated in the 1970's with work on S30400 and S31600 stainless steels. In some of this work S31600 stainless steel was partly embedded in concrete, exposed to stagnant, and to flowing seawater for 12.5 years. No corrosion was observed when the concrete was removed. Carbon steel samples exhibited corrosion and lost strength. Studies are also reported where S30200, S31500 and S31600 stainless steel were contained in precracked beams. After 10 and 20 years, these austenitic stainless steels did not reveal any cracking. Carbon steel samples cracked after six months exposure.[5]

The advantages in using stainless steel rebar are summarized Table I.

Applications for stainless steel rebar historically have included bridges for decks and overpasses, parapet walls and support structures as well as restoration projects, a few of which are listed in Table II. Multistory parking garages are also obvious candidates.

Actual applications, and quantities of stainless steel used in concrete structures are recorded in Table III.[6, 7]

ALLOYS

Various alloys have been employed, or considered, for reinforcing bars in concrete. Those to be considered here are: carbon steel, epoxy coated carbon steel, and stainless steels such as UNS S30400, S30453, S31600, S31653 and duplex S31803.

Alloying elements that could be found in stainless steel reinforcing bar are: carbon -

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strengthens the alloy; at elevated temperatures helps resist creep; low carbon, 0.03% is employed when welding and for improved corrosion resistance; chromium - about 11.5% chromium is required for a stable, passive, chromium oxide film to form and thus make the alloy "stainless"; chromium up to 26%, along with molybdenum and nitrogen, increases corrosion resistance to initiation of pitting and crevice corrosion; molybdenum - enhances resistance to initiation and propagation of pitting and crevice corrosion; nickel - improves general corrosion resistance, ductility, toughness, strength, enhances resistance to the propagation of pitting/crevice corrosion; assists in defining the alloy structure; nitrogen - enhances pitting/crevice corrosion resistance particularly in combination with chromium and molybdenum; increases strength of the steel.

MECHANICAL AND PHYSICAL PROPERTIES

The objective here is to relate some features of carbon steel rebar and the more corrosion resisting nickel chromium stainless steels to enable specifiers to have a ready reference to compare various aspects of reinforcing bar alloy.

Mechanical properties vary considerably depending on thermo-mechanical processing at any given mill. Mechanical properties, may therefore be different in the as-delivered condition from those noted in this document. A Certified Mill Test Certificate, is a key document to assure the product meets specification requirements. Life Cycle Cost should also be considered in addition to material/installed costs in all financial calculations.

Table IV will be the reference point for properties relative to this section.

Tensile Strength. The maximum load a material can withstand, without fracture, determines its tensile strength. Carbon steel, for rebar applications, is produced with a tensile strength of about 540 MPa (78 ksi)[8]. The stainless steels in the 300 series can be cold worked about 10% to match this strength. The duplex stainless steel in its annealed, or fully relaxed condition meets this strength level easily.

Yield Strength. The yield strength which is the load necessary to deform a material using 0.2% offset, is typically 400 MPa (58 ksi) minimum, for carbon steel reinforcing bars.[8] This is easily met with 10% cold worked stainless steel and is exceeded with the duplex alloy. Cold working stainless steels to higher levels would raise the tensile strength and in the case of the yield strength to 1,380 MPA (200 ksi) if required.

Elongation. Cold worked carbon steel possesses an elongation of about 25%. The duplex stainless steel noted would be no less ductile, while the other stainless steels noted exhibit improved ductility up to 40% in the annealed condition.

Hardness. This is the resistance of a metal to indentation, scratching, abrasion, or cutting and is associated with strength, wearability and resistance to erosion. The 300 series stainless steels compare favourably with carbon steel rebar in this regard; duplex stainless steel exceeds the value for carbon steel and thus improves on this feature.

Table V represents data that follows.

Coefficient of Thermal Expansion (CTE). The value for this property expresses the fractional increase, or decrease in length, compared to the original length, as the temperature increases or decreases respectively. The 300 series stainless steels have CTE's

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about 50% greater than for carbon steel. However, the duplex alloy CTE very closely approximates that of carbon steel.

Modulus of Elasticity. This characteristic is a measure of stiffness, or rigidity of a metal helping to define its deflection, or bending, in use. All alloys listed in Table V are in the 190,000 to 205,000 MPa (28- to 30-million psi) region.

Magnetic Characteristic. The 300 series stainless steels are nonmagnetic. UNS S30400 could change a portion of its structure to a magnetic phase during cold work. If this could be a problem, higher alloy S31600 would be preferred to prevent the magnetic footprint from taking place.[9] This is important where minesweeper ships are degaussed and where MRI (Magnetic Resonance Imaging) is employed as a medical diagnostic tool. The duplex alloy and carbon steel are magnetic.

Formability. All alloys noted can be formed with the same relative ease.

Corrosion Resistance. Oxide on carbon steel reinforcing bars in the form of rust requires about seven times greater volume than the original bar. As rust forms it places pressure on the concrete leading to cracking or complete loss of the concrete as spalling. In many cases costly repairs are required after a decade or two. The presence of chloride from road salt to remove ice or in a marine environment accelerates corrosion of carbon steel.

General corrosion resistance of stainless steel employed in concrete is very good. An oxide forms on the alloy that is thin and protective. If the oxide is removed during installation or otherwise scuffed, it reforms immediately. No pressure is exerted by this oxide on the concrete such as is found with carbon steel and rust.

Pitting due to chloride from salt. Although never used on its own, the Pitting Resistant Equivalent Number (PREN) as it is called, is calculated to give a relative pitting indication. As the chromium, molybdenum and nitrogen content in a nickel containing stainless steel is increased, so too does the Pitting Resistant Equivalent Number. From Table V, we could anticipate improved pitting resistance from the austenitic stainless steels with the duplex alloy exhibiting the best resistance, for the alloys shown, to the penetrating effect of the salt chloride ion. If the threat of pitting is reduced, via improved alloy selection, this helps offset the threat of decreased fatigue resistance also as there would be no pit stress riser. Carbon steel has no inherent pitting resistance, and thus, general corrosion (rust formation) and stress risers are candidate problems.

Cost Comparison. The cost ratio for the alloys illustrated in Table V suggest that for strength, corrosion resistance to pitting and crevice corrosion, a duplex alloy is cost-effective.[10]

Concrete Inhibitors. Concrete inhibitors, employed in carbon steel rebar structures, represent an additional cost of about $30 US per cubic metre of poured concrete.[11] Stainless steel does not require an inhibitor.

Water Membrane. If a membrane is utilized for carbon steel concrete structures, the preparation, smoothing and application of the membrane take time (added cost), and, temperature control is required for the setting concrete. Here, the added cost is about $24 US per square metre of surface put down.[11] With stainless steel, membranes are not needed.

Stress Corrosion Cracking. Work being conducted by the National Research Council Canada addresses the chloride induced corrosion behaviour of prestressed stainless steel

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rebar in chloride contaminated concrete. Here, carbon steel, stainless steel UNS S24000, S30400, S31600, and S31803 were introduced to the program. The concrete mix was cement/sand/aggregate ratio of 1:2:3 by mass. Cement was Type 10 Portland used for all samples with a water cement ratio of 0.50. Samples were cured at 25^0C and 100% RH for 28 days before being placed in the test environment. To simulate construction practice U-bent samples (bend radius 4 times bar diameter) were employed. Chloride levels of 0%, 0.5% and 2% and test program environments are exhibited in Table VI.[12] Carbon steel embedded in concrete cracked in 4 months. No cracking of the concrete has occurred with embedded stainless steel after two years and no corrosion of the U-bent reinforcing bar was observed.

Some samples were placed in an environmental chamber with a relative humidity of 80% and temperature cycles between 25^0C and 65^0C. Table VII reveals test results for this portion of the program. Carbon steel embedded in concrete with 2% chloride cracked in 4 months. No cracking of concrete or corrosion has occurred with embedded U-bent stainless steel reinforcing bar samples after two years. Samples were examined August 1998. The test programs continue.

Galvanic Corrosion. Where a combination of carbon steel and stainless steel is specified for a structure there has been considerable interest in the galvanic coupling of dissimilar alloys. Should the two alloys be in contact in air there could be concern for corrosion.

In concrete tests have shown the corrosion potentials of carbon and stainless steel are practically identical. If the surface area of the carbon steel is large compared to stainless steel the effect is insignificant. For the Schaffhausen Bridge, Switzerland, stainless steel was positioned at the outer level on the bridge supporting beams, vertical and supporting pylons. Carbon steel was used for the balance of the reinforcement. Designers did not consider it necessary to use a separating barrier.[13]

H.A. Webster addressed this question and determined that corrosion could take place if dissimilar metals are in contact. Prevention of metallic paths that transfer electrons between an anode and cathode will eliminate corrosion damage due to galvanic action.[14]

LIFE CYCLE COST (LCC)

Critical performance requirements such as durability to resist the effect of atmospheric corrosion and de-icing salts over the life of the structure, structural integrity to be maintained for the full design life and minimal maintenance must be met.

Stainless steel reinforcing bar increases the overall project cost one to fifteen percent for bridges depending on complexity of the structure.[2] Although initial costs are important, Life Cycle Cost calculations are necessary to reflect cost comparison of a structure. Figure 2 is the actual cost comparison for the Öland Bridge, Sweden.[10] Stainless steel alloy cost lines for S30400 and S31600 are expected to remain flat, indicating no additional cost for 120 years. By comparison, it is anticipated that a concrete structure with carbon steel will need restoration in about 18-23 years.

Table VIII exhibits detailed Life Cycle Cost calculations for the Schaffhausen bridge crossing the Rhine river in Switzerland. All the performance requirements noted had to be met for 80 years. For this work stainless steel S30400 was selected. The LCC calculations

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employed show that for the three materials studied, structural costs for stainless steel were about 14% less.

CONCLUSIONS

The use of stainless steel for concrete reinforcement is an established practice with specifications in place.

Stainless steels offer the same or higher strength levels than carbon steel, depending on the alloy selected. These alloys possess inherent corrosion resistance and feature good general, pitting, crevice corrosion resistance and stress corrosion cracking resistance. This family of alloys can be easily formed into 3d bends if required, welded, are available in magnetic or nonmagnetic alloy compositions, and has good high and low temperature strength characteristics. Galvanic effects are not a problem for stainless steel.

Life Cycle Cost calculations and forecast of stainless steel to last more than 120 years means cost-effectiveness. Restoration work required in the 20-year time period for carbon steel reinforcement, environmental impact of longer journeys, delivery delay, more fuel burned as vehicles sit at idle, added cost in drilling, blasting, crushing and transport of aggregate, cement and the attendant power units to manufacture these items all must be considered in calculating costs.

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Table I

Advantages of Nickel Chromium Stainless Steels

! Good tensile/yield strength to match, or exceed, that of carbon steel.
! Inherently good corrosion resistance, especially to environments with chloride from marine and road salt.
! Magnetic or nonmagnetic, depending on alloy and application.
! Life Cycle Cost (LCC) advantages for the concrete structure - some stainless steel calculations employ lifetimes up to 125 years. Carbon steel restoration about every 20 years or so for bridges or elevated highways, result in disruption costs, missed just-in-time deliveries, highway rerouting and other commerce delays, which are costly. If all the costs are factored into LCC calculations, stainless steel comes out favourably.
! Good weldability.
! Good ductility (capable of 3d U-bends).
! No coating to chip, crack, corrode or repair.
! No cut ends to coat, cover or insulate.
! Good high and low temperature mechanical properties.
! Can be shipped, handled, bent without a problem.
! Depending on the stainless steel selected, an almost identical match for coefficient of thermal expansion.

Table II

Applications for Nickel Containing Stainless Steels

! Bridges for decks and overpasses, parapet walls and support structure.
! Restoration projects.
! Parking garages for deck, walls and support columns.
! Footings for buildings, support walls, floors and columns.
! Marine structures for wharf, piers, sea wall protection, dock areas both commercial and military (degauss of minesweepers).
! Offshore platforms.
! Process industry, where chemicals could cause corrosion of carbon steel.
! Medical, for Magnetic Resonance Imaging systems where nonmagnetic stainless steel is a prerequisite.
! Sanitary and water facilities for water intake, storage and handling waste water.
! Restoration projects utilize stainless steel for corrosion resistance, strength and long life.
! Rock anchors, dowels for concrete slabs, tie bars, couplers, post tension bars.

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Table III

Actual Applications

- Australia - Christ Church, Newcastle, restoration earthquake zone; Sydney Opera House, promenade, marine 14 tonnes S31600 stainless steel.
- Canada - Highway 407 bridge deck 11 tonnes S31653, in addition about 310 tonnes stainless steel rebar will be utilized in 1998 and an additional 560 tonnes in 1999 for other bridge projects in Ontario.
- Denmark, Great Belt Connection, earthing rods and wires for making electrical connections to reinforcement.
- Sweden - Öland Bridge.
- Switzerland - Schaffhausen bridge.
- United Kingdom - Cambridge University/Bio-Technology Laboratory; Emmanuel College, Cambridge, post tensioned bars; foundation supports, Mansion House, London; Guildhall Yard East, restoration; Mersey Tunnel; M4 Motorway bridge reconstruction 27 tonnes S30400; Manchester Airport, slab dowels; underpass near Newcastle , 240 tonnes S31600; Rock anchors A55, North Wales; Scarborough Spa, marine; St. Paul's Cathedral, restoration; Thames Bank at Wapping, brick faced precast concrete panels; tie bars with couplers, bridge strengthening.
- United States - bridge deck, Trenton, New Jersey; Bridge deck; Detroit, Michigan, Bridge deck S30400; Brush Creek Bridge, Oregon, 75 tonnes S31653; New Jersey Garden State Parkway and Route 80, 160 tonnes duplex alloy UNS S31803.

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Table IV

Mechanical Properties of Some Reinforcing Bar Alloys

Alloy	Tensile Strength MPa (ksi)	Yield Strength as rolled, MPa (ksi)	Elongation % in 2 in. typical minimum values	Brinell Hardness
Carbon Steel	540 (78)	400 (58)min	25	200
Carbon Steel epoxy coated	540 (78)	400 (58)min	25	200
S30400 stainless steel	750 (108) ~10% cold work	600 (87)	37	200
S30453 stainless steel	730 (106) ~10% cold work	500 (73)	37	200
S31600 stainless steel	810 (117) ~10% cold work	520 (75)	40	220
S31653 stainless steel	690 (100)[15] ~10% cold work	523 (76)	16	250
Duplex S31803	680 (99) no cold work	480 (70)	25	290

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Table V

Physical Properties of Some Reinforcing Bar Alloys

Alloy	Coefficient of Thermal Expansion 20-1000C µm/mm/^{0}C (µin./in/^{0}F)	Modulus of Elasticity X 10^3	Magnetic	Corrosion Resistance General/Pitting	PREN Pitting Resistance Equivalent Number	Approx. Cost Ratio 1996
Carbon Steel	11.7 (6.6)	205MPa (30ksi)	yes	poor/poor	- - -	1.0
Carbon Steel epoxy coated	11.7 (6.6)	205MPa (30ksi)	yes	poor/poor	- - -	1.7 - 2.0
S30400 stainless steel	17.0 (9.5)	200MPa (29ksi)	no	good/fair	18	3.8
S30453 stainless steel	16.8 (9.4)	200MPa (29ksi)	no	good/fair	21	4.3
S31600 stainless steel	16.5 (9.2)	200MPa (29ksi)	no	good/better	25	4.4
S31653 stainless steel	16.5 (9.2)	200MPa (29ksi)	no	good/better	27	4.7
Duplex S31803	13 (7.3)	190MPa (28ksi)	yes	very good/very good	36	4.4

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Table VI

Carbon Steel and Stainless Steel Reinforcing Bar Test Results After 2 Years

	Alloys					Environment			
Test Program	Carbon Steel	S30400 Stainless Steel	S31600 Stainless Steel	Duplex S31803	S24000	Temp. ^{0}C	Relative Humidity	Time of Test	Test Results
Test #1: Temp. Cycling	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	Daily cycling between 25^{0}C and 65^{0}C	80% RH	Since August 1996	Carbon steel samples in 2% Cl^- cracked; minor corrosion on carbon steel in 0.5%Cl^-; no corrosion on stainless steel.
Test #2: Constant Temp.	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	0%Cl^- 0.5%Cl^- 2.0%Cl^-	Constant Temp. at 35^{0}C	95% RH	Since February 1997	Some samples opened in August 1998. No corrosion.
Test #3: Immersion	0%Cl^-	0%Cl^-	0%Cl^-	0%Cl^-	0%Cl^-	Ambient	Immersed in 3.4% NaCl	Since February 1997	Electrochemical test no corrosion at this stage.
Test #4: 3.4% NaCl Ponding ASTM G-109	0%Cl^-	0%Cl^-	0%Cl^-	0%Cl^-	0%Cl^-	Ambient	3.4% NaCl solution - ponding	Since February 1997	Electrochemical test no corrosion at this early stage.

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Table VII

80% Relative Humidity; Temperature Cycled Between 25 and 65^{0}C; Examination After Two Years; No Effect from Thermal Expansion

	Concrete Sample Condition	Rebar Condition
Carbon Steel		
0.5% Chloride	no cracking observed	no significant corrosion observed
2% Chloride	severe cracks, all samples broken after 4 months	severe corrosion on entire rebar
304 Stainless Steel		
0.5% Chloride	no cracking observed	no corrosion observed on rebar
2% Chloride	no cracking observed	no corrosion observed on rebar
316 Stainless Steel		
0.5% Chloride	no cracking observed	no corrosion observed on rebar
2% Chloride	no cracking observed	no corrosion observed on rebar

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Table VIII

Life Cycle Cost (LCC) for Schaffhausen Bridge - 1997[16]

RATES AND DURATION

Cost of Capital:	9	%
Inflation Rate:	3.5	%
Desired life cycle duration:	80	years
Downtime per maintenance/replacement event:	120	days
Value of lost production:	34,484	†Mu/day
Real Interest Rate:	5.31	%

APPLICATION INFORMATION

Unit: Bridge at Schaffhausen	
Material 1:	Carbon Steel
Material 2:	Epoxy Coated C.S.
Material 3:	Stainless Steel

†Mu = 1 US dollar

INITIAL COSTS

Material Costs (Mu)	Carbon St	Epoxy C.S.	Stainless Steel
Plate, sheet	0	0	0
Pipe, fittings	0	0	0
Bar and other (fittings, consumables)	5,653	21,670	61,138
Fabrication and Installation Costs (Mu)			
Cutting, welding, forming, etc.	0	0	0
Assembly and installation	10,766,918	10,766,918	10,766,918
Other Installation Costs (Mu)			
Surface protection	0	0	0
Special labour skills, etc.	0	0	0

OPERATING COSTS

Maintenance Costs (Mu)	Carbon St	Epoxy C.S.	Stainless Steel
Cost per event (Mu)	0	0	0
Elapsed time between events (years)	25	25	80
Replacement Costs			
Removal costs per event (Mu)	0	0	0
Material and installation costs per event	477,952	143,386	0
Residual value of material per event	0	0	-6,114
Elapsed time between events (years)	25	25	80
Material-related Operating Costs			
Annual cost (Mu)			

LIFE CYCLE COST SUMMARY OF A RIVER CROSSING HIGHWAY BRIDGE

Description	Carbon St	Epoxy C.S.	Stainless Steel
Material costs	5,653	21,670	61,138
Fabrication costs	0	0	0
Other installation costs	10,766,918	10,766,918	10,766,918
Initial costs (Mu)	10,772,571	10,788,588	10,828,055
Maintenance	0	0	0
Replacement	176,724	53,017	-97
Lost production	1,530,083	1,530,083	0
Material related	0	0	0
Operating Costs (Mu)	1,706,807	1,583,100	-97
Total LCC (Mu)	12,479,378	12,371,688	10,827,958

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Figure 1. Corroded carbon steel reinforcing bar in elevated roadway of Gardner Expressway, Toronto, Canada

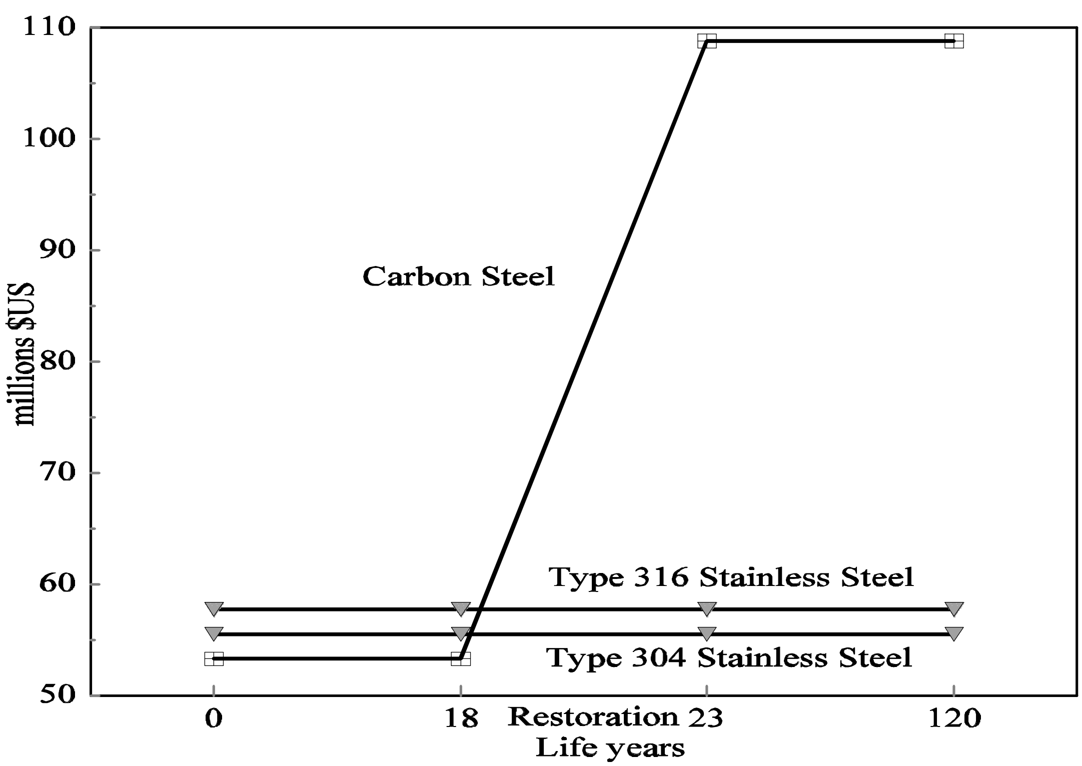

Figure 2 Life Cycle Cost Figures for Oland Bridge, Sweden

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