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The effects of corrosion rate and manufacturing in the prevention of stress corrosion cracking on structural members of steel bridges

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Abstract

The effects that stress corrosion cracking is having on the structural steel members in bridges is costing the US Government billions of dollars a year and putting hundreds of lives in danger. There are already a variety of ways to prevent stress corrosion cracking that have had some success, though are still limited. Stress corrosion cracking is the result of corrosion combined with stresses in the steel. This paper is based on structural steel S275. The solutions proposed in this paper are to reduce the corrosion rate by changing the chemical composition of the steel, and to reduce the stresses in the steel changes in the manufacturing processes have been proposed. The combination of these solutions will contribute to the reduction in the effects of stress corrosion cracking on steel S275.

Keywords: Stress Corrosion Cracking, Steel S275, Corrosion Rate, Silicon, Nickel, Hydrogen Embrittlement, Bridge.

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1. Introduction

The effects that corrosion and corrosion related issues, are having on bridges is costing the US government billions of dollars each year. This includes an estimated $3.8billion for bridge replacement and $0.5billion for the maintenance of steel bridges, along with the estimated loss of £38billion due to travel delays 'Cook, D. C [1]'. This is all because of the on going struggle to prevent/reduce the rate of corrosion in a harsh environment as the majority of these bridges are over water. The effects of ever changing environmental conditions can have a big effect on corrosion, this can be seen in work by 'Saeed, A [2]'.

The corrosion on bridges can have disastrous consequences, as the increasing amounts of corrosion can weaken the structure of the bridge resulting in the failure and collapse of the bridge often due to the formation of stress corrosion cracking. This can have horrendous results as seen in the collapse of U.S. Highway 35 (Silver Bridge) in 1967, that claimed the lives of 46 people and seriously injured 9 people 'Corrosion Doctors [3]'. More recently the collapse of the I-35W Bridge in Minnesota claimed the lives of 13 people and left 145 injured 'Popular Mechanics [4]'.

The types of corrosion that have been identified to occur on the structural members of bridges are surface corrosion and pitting corrosion 'Kayser, J. R [5]'. The effects of surface corrosion along with minor defects in the surface can lead to Pitting corrosion and in turn leading to stress corrosion cracking 'National Physics Laboratory [6]' causing the failure of the bridge. Thus the prevention of surface, and in turn pitting, corrosion will be of high priority. Along with the reduction in corrosion to prevent stress corrosion cracking, the processing of the steel during manufacture will need to be looked at to aid in the prevention of stress corrosion cracking.

The steel used for bridges is structural steel grade S275 conforming to standard BS 10025 'West Yorkshire steel [7]' 'SteelConstruction.info [8]. This will be considered and used in the writing of this paper and the demonstration of the solution. Properties of the steel S275 can be seen in section 5.

This paper will look into and analyze the relationship between the chemical properties of the steel and the effect that it has on the corrosiveness of the steel, in order to prevent stress corrosion cracking. The manufacturing process of the steel will be looked into and how it too could aid in the prevention of stress corrosion cracking. Another area to be looked at will be the change in the chemical composition reducing corrosion, against the change it has on the mechanical properties of the steel. There are already methods of

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corrosion prevention, which will be critiqued to provide a comparison to the solution being proposed in this paper. As this is a commercial application cost will be a factor that is taken into consideration in relation to any benefits gained from the reduced corrosion.

2. Atmospheric corrosion theory

Atmospheric corrosion accounts for the most failures, “about 80% from all degradations produced by corrosion in the metallic constructions are due to atmospheric corrosion” ‘Badea, G. E [9]’. Atmospheric corrosion is often split into three classifications: dry oxidization, damp corrosion or wet corrosion ‘Shreir, L. L [10]’. As most bridges are over water the most common type of corrosion to occur will be damp or wet corrosion. This is where a film of electrolyte solution is covering the surface of the metal, this electrolyte is not always visible. The levels of humidity will affect the presence of the electrolyte, but approximately humidity above 60% will cause this electrolyte film to occur on the metal surface ‘Badea, G. E [9]’.

The underlying theory of corrosion is the loss of electrons from the anode to the cathode, which causes oxidization of the metallic atoms. For corrosion on the steel bridges the reaction uses the steel as the anode and the electrolyte film, form the damp/wet corrosion theory, as the cathode.

3. Existing corrosion prevention

A cathodic protection system uses a secondary metal, in electrical contact, which is more corrosive when looking at the galvanic series. This uses a sacrificial anode that will corrode before the steel of the bridge due to the potential difference between the metals. ‘Sacrificial cathodic protection system’ was patented in 1983 ‘Maes, J. P [11]’.

Galvanic protection is similar to cathodic protection as it uses a sacrificial anode that will corrode before the protected metal does ‘Bushman, J. B [12]’. Though galvanization is applied to the whole surface of the metal; also creating a physical barrier between the steel and the atmosphere. It was first recorded in 1853 the meaning of galvanize to mean, “coat with metal by means of galvanic electricity” ‘Dictionary.com [13]’.

A method commonly used is to paint the steel of the bridges, this creates a physical barrier between the steel and the atmosphere preventing corrosion. This is a very simple but effective method of preventing corrosion.

4. Identification of problem

Cathodic and galvanic protection systems both are viable options for protecting the steel structural members of bridges. Though they have their limitations, as the sacrificial anode will still corrode, and at a quicker rate than the steel would have. Once these sacrificial anodes become corroded to a thresh hold level they will no longer protect the steel from corrosion and the steel will corrode as it would have without the protection. In relation to the sacrificial cathodic protection system 'Maes, J. P [11]' the sacrificial anodes would have to be changed regularly to maintain the effects of preventing corrosion of the steel. The need to regularly change the anodes would be very expensive so for the use on bridges it would be costly. As well the current capacity of anodes can have limitation in relation to their size meaning the performance of corrosion resistance would be limited.

Painting the steel is the most often used method of preventing corrosion of steel bridges, as it is cheaper and simpler to use than cathodic or galvanic protection, however this too comes with its limitations. In theory the paint will create a physical barrier between the atmosphere and the steel preventing corrosion. Failures can still occur in the paint coating, such as blistering or pealing, this can be due to the incorrect coating being used or the improper surface preparation of the steel 'Tombaugh, R. S [14]'. Painting of the steel can actually cause more damage due to corrosion, this is due to the failures in the painting. Small breaks in the painting surface can allow the exposure of the steel to the atmosphere, causing concentrated and accelerated corrosion in these areas in the form of pitting corrosion 'Frankel, G. S [15]'. In turn the pitting corrosion can result in stress corrosion cracking that could cause catastrophic failure in the steel structural members.

The problem that has been established is the difficulty in preventing corrosion on the steel structural member of bridges. This is very serious as when corrosion reaches certain propagation level it can weaken the structure integrity of the steel and lead to stress corrosion cracking, resulting in possible failures of the bridge. Failures on the scale of bridges doesn't only cost the US government billions of dollars but also put lives in danger 'Cook, D. C [1]'. Corrosion to bridges is a major problem in the US, and around the world. This is seen from the catastrophic failure of the I-35w bridge which, "In1990, the federal government gave the I-35W bridge a rating of "structurally deficient," citing significant corrosion in its bearings. The bridge is one of about 77,000 bridges in that category nationwide" 'MPRnews [16]'.

Stress corrosion cracking is a "combination of static tensile stress and corrosive environment" 'Eliaz, N [17]'. Thus reducing the corrosion on the structural members of the bridge will reduce the probability of stress corrosion cracking. The presence of pitting corrosion is significant as it creates a weak point in the steel allowing for the development of a high concentration of stress where a crack is more likely to occur. Another factor that can have an effect on the development of cracks in the structure is Hydrogen Embrittlement (HE), the combination of the hydrogen in the steel, coupled with the stress being applied to the steel. "Internal HE by the mechanism of high-pressure bubble formation might be extremely severe due to the ease of cavity (microcrack) growth" 'Eliaz, N [17]'. Thus these microcracks can increase the possibility of stress corrosion cracking and assist in the failure of the metal by possibly making cleavage easier or assisting in intense localized plastic deformation 'National Physics Laboratory [6]'. The effects of the unpredictable environmental conditions make it difficult to present viable corrosion resistance solutions. With most bridges being over water they are affected by the harshness of marine atmospheric corrosion conditions. Not only is the bridge under static stress due to the weight of the bridge but also dynamic loading created by the movement of the vehicles, this further complicates things and increases the probability of a crack forming.

Corrosion rates can differ depending on the location of the bridge, the atmospheric conditions, the rain fall, whether or not the bridges are over fresh water or salt water and many other uncontrollable variables. The corrosion rate in the marine atmospheric environment can be between10-30μm/year 'Cicek, V [18]' others state up to 0.05-0.10mm/year 'Melchers, E. R [19]'. In this paper it is the percentage in reduction of corrosion that is relevant, thus for this paper the corrosion rate of 30μm/year will be used.

The proposed solution being investigated is to change the chemical composition of the steel during the manufacturing stage to reduce the rate of corrosion when in use. Research has already been done into the effect of changing the levels of carbon (C) content, which shows a minimal change in the corrosion rate 'Melchers, E. R [20]'. This paper will investigate the effects of changing the percentage levels of Silicon (Si) and Nickel (Ni) in relation to the effects this has on the corrosion rate of the steel. Previous evidence from 'Saeed, A [21]' shows that silicon has an effect on corrosion, though these tests were on aluminum alloys, never the less this shows promise for the effects of increased Silicon.

5. Result findings and Evaluation

The proposed solution will be to increase the corrosion resistance of the steel, thus reducing the probability of stress corrosion cracking, by increasing the levels of Silicon (Si) and Nickel (Ni) in the steel. The first study is into the effect increased Silicon has, the second being the effect Nickel has, both in relation to the corrosion rate of the steel. The control will be Steel S275, which has the chemical composition shown in Table 1 'Database of Steel and Alloy (Marochnik) [22]'. The corrosion rate used will be 30μm/year, this is the corrosion rate of steel in the marine atmospheric environment.

C	Si	Mn	Ni	S	P	Cr	N	Cu	Fe
0.22%	0.1% Si	0.65%	0.3%	0.05%	0.04%	0.3%	0.012%	0.3%,	98.028%

Table 1: Chemical composition of steel S275

A steel sample was placed in a marine atmospheric environment, "Located 250 meters from the Atlantic Ocean, this site is a moderate marine site" 'Kirk, W. W [23]'. This is a similar atmosphere in which most bridges are exposed to. The effects were, for each 0.1% increase in Silicon resulted in a 10.83% decrease in corrosion rate, also a 0.1% increase in Nickel resulted in a 9.9% reduction in corrosion rate 'Kirk, W. W [23]'. This data will be used to extrapolate result of increasing Silicon and Nickel in relation to the corrosion rate.

Silicon % content	Corrosion rate µm/year
0.1	30
0.2	26.75
0.3	23.85
0.4	21.27
0.5	18.97
0.6	16.91
0.7	15.08
0.8	13.45
0.9	11.99
1	10.69
1.1	9.53
1.2	8.50
1.3	7.58
1.4	6.76
1.5	6.03
1.6	5.38

Table 2: Corrosion rate of Silicon content

Table 2 shows the prediction of the increase in Silicon content and the effect it has on the corrosion rate of steel S275. In order to more clearly demonstrate the change in corrosion rate compared with the increase in Silicon the data has been put into a graph (Figure 1).

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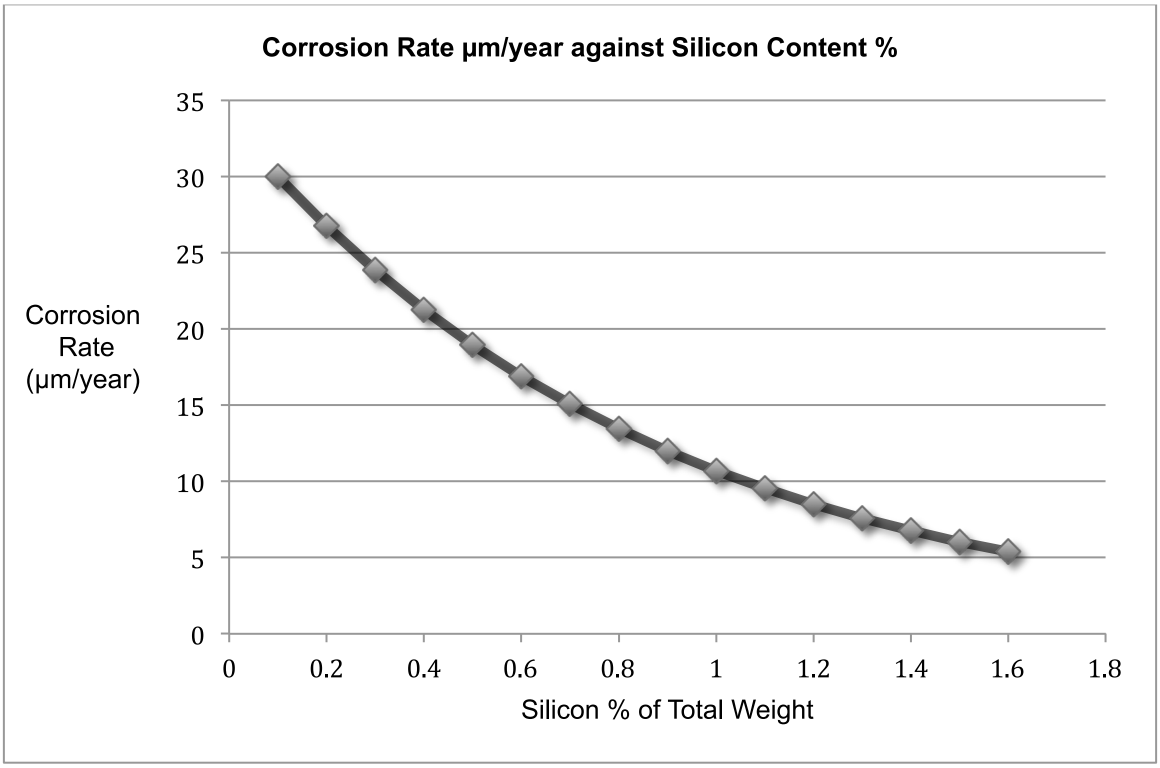

Figure 1: Graph to show corrosion rate / Silicon content

This graph shows a strong correlation between the percentage content of Silicon in the steel and the effect it has on the corrosion rate. The correlation is inversely proportional, as the percentage of Silicon in the steel increases the corrosion rate decreases. Though the relationship is exponential not linear, thus the benefits of each 0.1% increase in Silicon is reduced after each iteration. The data shows that a 0.6% increase in the Silicon content will cause a 50% reduction in the corrosion rate. The graph could be extrapolated to show the effects of higher levels of Silicon, though the effects of this further increase in Silicon would have minimal effect on the corrosion rate in µm/year.

The question of the effects of the increase in the percentage of Silicon in the steel is a significant factor. A study was done by 'Garrison, W. M. Jr [24]' on the effects of the increase in Silicon content in steel. This study showed that when 1.9% Silicon was added to steel it had no adverse affects on the mechanical properties of the steel, if anything it improved the properties slightly. The added Silicon increases the strength and hardness of the steel. Though the increase of Silicon to the steel does come with some unfavourable characteristics. Reduction in the ductility of the steel making it more brittle, this is not desirable when under tensile stress and dynamic loads that occur in bridges. The other effect of the increased Silicon content makes it difficult to weld the steel 'leonghuat [25]

Nickel % content	Corrosion rate µm/year
0.3	30
0.4	27.03
0.5	24.35
0.6	21.94
0.7	19.77
0.8	17.81
0.9	16.05
1	14.46
1.1	13.03
1.2	11.74
1.3	10.58
1.4	9.53
1.5	8.59
1.6	7.74
1.7	6.97
1.8	6.28

Table 3: Corrosion rate of Nickel content

Table 3 shows the prediction of the increase in Nickel content and the effect it has on the corrosion rate of steel S275. In order to more clearly demonstrate the change in corrosion rate compared with the increase in Nickel the data has been put into a graph (Figure 2).

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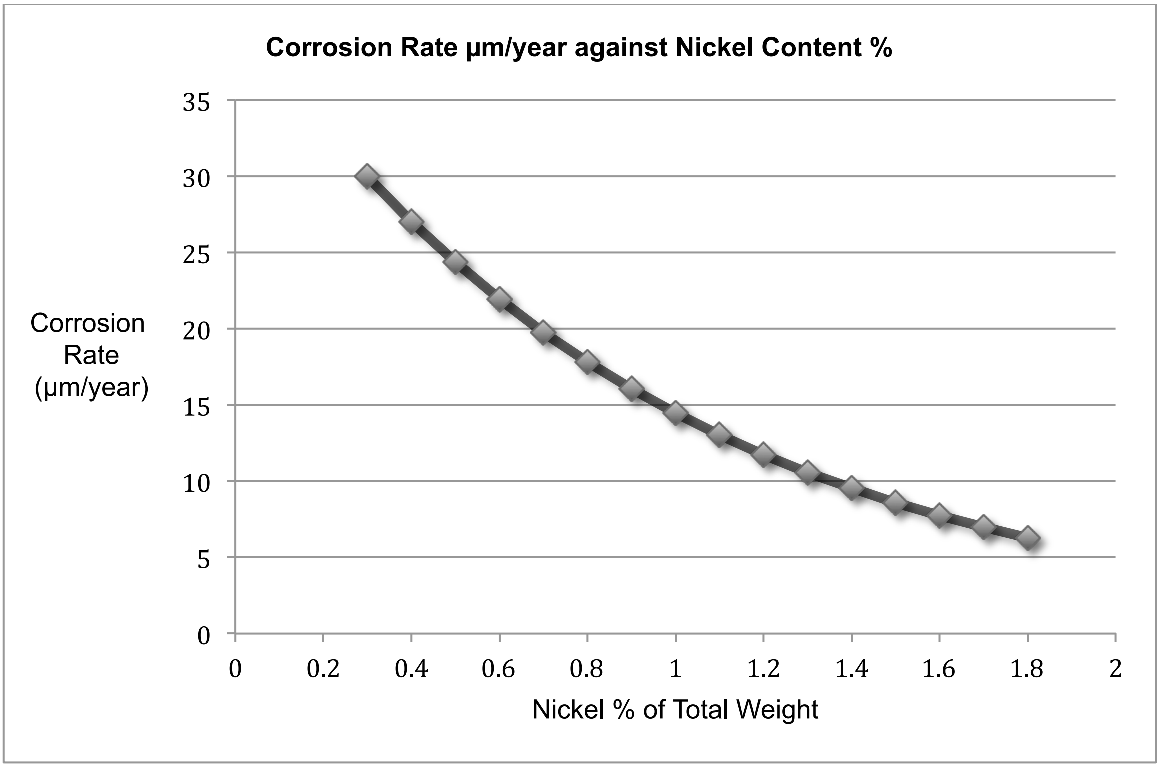

Figure 2: Graph to show corrosion rate / Nickel content

This graph shows a strong correlation between the percentage content of Nickel in the steel and the effect it has on the corrosion rate. The correlation is inversely proportional, as the percentage of Nickel in the steel increases the corrosion rate decreases. Though the relationship is exponential not linear, thus the benefits of each 0.1% increase in Nickel is reduced after each iteration. The data shows that a 0.7% increase in the Nickel content will cause over a 50% reduction in the corrosion rate. The graph could be extrapolated to show the effects of even higher levels of Nickel, though the effects of this further increase in Nickel would have minimal effect on the corrosion rate in µm/year.

Whilst increased levels of Nickel reduce the corrosion rate it is important to consider what effect increased Nickel would have on the steel. A study was done by W.M.Garrison, Jr. [24] into the effects of the increase in Nickel content in steel. This study showed that when 1.5% Nickel was added to steel it had minimal adverse effects on the mechanical properties of the steel. The only mechanical properties that were affected were the 'Yield strength' and the 'Ultimate tensile strength', regardless these properties were only reduces by less than 7%. Though increasing the percentage of Nickel in steel causes the toughness and fatigue resistance of the steel to increase 'Bright Hub Engineering [26]'. The downside to adding more Nickel to the steel is the added weight, which is undesirable when used in the construction of bridges 'Process Industry Forum [27]'.

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The factor of cost needs to be included in the decision-making. The cost of the Nickel is approximately $14 per kg 'MetalPrices.com [28]' compared to Silicon, which costs roughly $2.75 per kg 'MetalPrices.com [29]'. This shows that the addition of Silicon is financially the more desirable option, as it is a fifth of the price of Nickel.

Along with the reduction in corrosion to help prevent the effects of stress corrosion cracking, there are processes that can be preformed during the manufacturing to reduce the probability of stress corrosion cracking occurring. To reduce internal stress, stress relief annealing should be used. This will be preformed by heating the steel to between 600-750˚C, then allowing it to cool slowly 'Totten, G. E [30]'. By doing this it will relieve the internal stresses, which are created during the manufacture of the steel, reducing the probability of cracks occurring. Low temperature annealing can be performed to reduce the probability of Hydrogen Embrittlement that can also contribute to stress corrosion cracking. This is done by heating the metal in an annealing oven for several hours at between 190-220˚C 'Herring, D. H [31]', causing the hydrogen to be removed from the steel. In cases of very large bridges these processes would not be practical for every section of the bridge, thus these processes would be preformed on areas that are identified to be under greatest stress such as joints and welds.

6. Conclusion

The harsh atmospheric environment that the structural members of bridges are subjected to makes it very difficult to prevent stress corrosion cracking from occurring. Though some success has been achieved by using a galvanic coating or painting the steel, unfortunately these prevention methods eventually fail resulting in the steel corroding. However this corrosion rate can be greatly reduced by the addition of either Silicon or Nickel. By adding 0.6% Silicon to steel S275 the corrosion rate will be reduced to 50% of the original corrosion rate and by adding 1.5% Silicon the corrosion rate would drop even further to only 18% of the original corrosion rate. Similar effects are seen with Nickel, by adding 0.7% Nickel to steel S275 the corrosion rate will reduce to 50% of the original corrosion rate and by adding 1.5% Nickel the corrosion rate would drop even further to 21% of the original corrosion rate. Though effective methods for reducing the rate of corrosion neither of these methods will completely eradicate the problem of corrosion. Along with the benefit of preventing corrosion, the addition of either element to the steel comes with unfavourable characteristics. Silicon does have an added benefit, by adding between 1.5%-2% of Silicon to the steel it is possible to suppress the kinetics of Tempered martensite embrittlement 'Hertzberg, R.W [32]'.

The other contributing factor to stress corrosion cracking is stresses that occur in the steel. These stresses could be reduced by stress relief annealing performed during the manufacture of the steel. Along with this Low temperature annealing would be performed during manufacture to reduce the Hydrogen Embrittlement.

In conclusion the addition of Silicon is the most favourable choice over the addition of Nickel as the Silicon has the greatest effect on reducing the corrosion rate. The increased percentage of Silicon in the steel has very little effect on the mechanical properties, and would be easier to design around any of the possible adverse effects resulting from the addition of the Silicon. The factor of money is taken into account with Silicon being greatly cheaper than Nickel. Further research could be conducted to investigate the ideal percentage of Silicon added to steel S275 for the application of bridge members and many other applications where steel S275 is used. Stress relief annealing and low temperature annealing will be performed during the manufacturing of the steel to reduce stresses in the steel. The increased Silicon combined with the heat treatment during manufacture, will aid in the prevention of stress corrosion cracking occurring in steel S275.

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