FEEG2005 Consultancy Report

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Abstract

In this document, I will analyse the failure mechanism of a piece of rebar that was used in a motorway. I will explain how the failure surface describes the loading conditions and what lead to the final failure. I will also make recommendations for how to avoid failure in the future.

1 Background

The raft that the rebar was in recently experienced subsistence, changing the loading conditions. This will have lead to reverse bending, as is visible in Figure 1. When a vehicle drives on the raft that was not affected by the subsistence, there will be a positive moment on the rebar. This leads to the bar bending downwards, as is shown in A. When the vehicle then moves onto the raft affected by subsistence, there will now be a negative moment on the rebar, as shown in B. In addition to this, the porosity of concrete means that when salt is used, corrosive fluids will be in contact with the rebar. This will lead to pitting and therefore stress concentrations as localised corrosion occurs. There will likely be electrochemical cells as some parts of the rebar will be surrounded by pores in the concrete but others will be surrounded by material. This will naturally lead to a difference in oxygen concentration and crevice corrosion.

An important equation for this report is the Goodman relation, shown in Equation 1.

$$\sigma_a = \sigma_{a0}(1 - \frac{\sigma_m}{\sigma_{ts}})$$

Where σ_m is the mean stress, σ_{ts} is the tensile strength, σ_{a0} is the fatigue strength at $\sigma_m = 0$ and σ_a is the fatigue strength. It is clear from this equation that as σ_m increases, σ_a must decrease assuming all else stays the same.

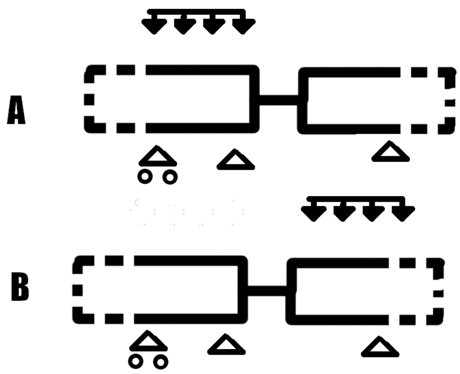
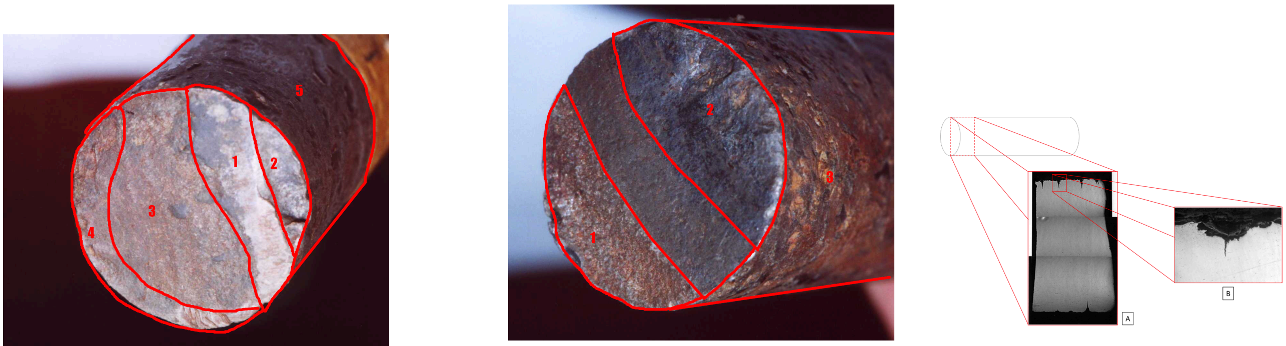


Figure 1: Diagram of how the loading conditions changed when a vehicle drives over a concrete raft

2 Fractography

It is clear from Figure 2 that the rebar was undergoing reverse bending. This is because the final fracture regions are on opposite sides of the rebar, visible in $a_{1,2}$ and b_1. There was also severe corrosion visible. This is evident through multiple methods, such as the large number of ratchet marks, labelled as a_4 and b_1. These indicate where other cracks started to grow on other planes, and then intersected the main plane. Many of these are visible on both of the fracture faces, indicating the large number of other crack initiation sites. In addition to this, Figure 2c shows a look down one of the sides of the rebar. It is evident that there is corrosion pitting in many places. In addition to this, there appears to be crevice corrosion, leading to the long thin cracks near the tip. These have a small tip radius, leading to a large stress intensity factor and faster failure. The extent of this corrosion is clear from a_5 and b_3, and the number of other corrosion pits makes it clear that the corrosion was a significant cause of the failure.



(a) The face that failed in service

(b) The face that was later cracked open by consultants

(c) Severe corrosion pitting visible on the outer face of the rebar

Figure 2: The faces of the samples of rebar

In Figure 2a, there is evidence of beech marks on a_3. These can be used to point back to the crack initiation sites, and indeed they point to the corrosion pits and ratchet marks in a_4.

When the subsistence occurred under the raft, this will have lead to the loading conditions going from mostly unidirectional bending to reverse bending. Because of this, the stress ratio will go from being positive initially from the constant dead load of the structure and the live load of vehicles and weather on top, to negative from the live load being both compressive and tensile. It is unlikely that this was accounted for in the design phase.

The relatively large final fracture regions from sites $a_{1,2}$ and b_1 show that σ_{nom} was relatively low. The fairly flat nature of the final fracture region indicates that there was no significant stress concentration. This suggests that the main role played by corrosion was initiating the crack, and after there was a crack there were no other significant effects played. This also indicates that the cross section of the rebar did not cause accelerated failure, and this makes sense because there are no tight radii or keyways visible. a_1 shows shear lips indicating that this was a ductile failure. Because the shear lips are always 45° to the maximum opening stress, it is fairly clear from the angle that the forces were not only tensile, further strengthening the argument for reverse bending.

3 Recommendations

To minimise the risk of failure reoccurring, a number of methods could be employed. The first method in response to fatigue failure is to try to reduce the fatigue the structural member is experiencing. However due to the nature of motorways, this is not feasible. This would either require removing the rebar from the concrete, which would severely hamper the concrete's ability to perform, or reduce the magnitude of stress fluctuations. Reducing the magnitude of stress fluctuations would most likely mean reducing the maximum weight of vehicles travelling on the motorway, which is only achievable after policy changes from Westminster. These all alter σ_m in Equation 1.

As corrosion was also an issue, there are a number of methods to tackle this. For example, austenitic or duplex stainless steels could be used instead of mild steel that is typically used in rebar [2]. This will obviously lead to higher costs though, as mild steel is typically cheaper than stainless steels [3]. On the other hand, there is more control over the localised corrosion rate based on the alloy composition [3]. In addition to corrosion resistance, σ_{a0} and σ_{ts} would likely change.

Another method is shot or laser peening. These put compressive stress at the top of the material so that it is harder for cracks to grow. Shot peening is cheaper, but does result in less protection, as laser peening means that the stresses reach further below the surface of the material. Carburisation could also be used, but as this is a time and temperature dependant process, this would be extremely costly. The surface would be harder, meaning that it would be harder for cracks initiate. This will not affect anything in Equation 1, however it will increase the amount of time spend in Regime A of the Paris Law.

The issue with all of the above solutions is the cost that they have. To treat 3736 kilometers [1] worth of material would be incredibly expensive, let alone the time needed to change the rebar, which would lead to major disruption. While they all individually work well for given situations, the scale of the motorway network means it is difficult to implement any one of them.

The best, most effective method is to reduce stress on each piece of rebar. Mean stress can drastically affect the mean number of cycles to final failure, so reducing this will prolong the life of existing rebar. There is already a large supply chain for existing rebar, meaning that costs will likely be reliable, and it does not add any additional complexities that may not be considered in the design phase. If the design stress is lower, σ_m is reduced, possibly by a large amount, and the lifespan will increase accordingly. In addition to this, regular inspections would help in the future. If the subsistence can be identified before it causes major problems, the lifespan of the rafts will be dramatically improved. The frequency of these inspections does need to be balanced against the cost of inspecting every mile of motorway, however.

References

[1] Department for Transport. *Road length in kilometers (RDL02)*, 2022.

[2] Types of steel – the most common types used in construction, Jan 2022.

[3] M. V. Vaghani. Stainless steel as a structural material: State of review. In *International Journal of Engineering Research and Applications*, 2014.