Potential Unintended Consequences Due to a Lack of Scientific Rigour

by Dr Angus Ramsay

Background

The author has written previously in this journal presenting in 2017 the concepts and importance of simulation governance and, in 2019, examples of the sort of work a structural engineering expert might undertake and how he/she can ensure, through simulation governance, that the results presented will withstand the sort of scrutiny likely to be seen under cross examination [1,2]. In this year's article I am going to present a case study from a recent project involving the repair of cracks found in a 30-year old overhead crane. Whilst interesting in itself from a structural engineering viewpoint, the project highlights the difficulty of assessing a situation where the facts are sparse and where opinion, not based on the scientific method, has the potential to lead to unintended consequences and costs.

Introduction

This case study comes from a recent commercial project undertaken by the author at his engineering consultancy, Ramsay Maunder Associates (RMA). The owner of the crane contacted RMA after a recent inspection had revealed cracks in some of the main structural members. The owner had employed a reputable crane maintenance organisation to repair the cracks. This included two aspects, firstly, the gouging out and welding up of the crack and, secondly, the welding of a cover plate over the previously cracked region. The insurer of the crane asked the owner to provide confirmation that the stresses under and adjacent to the new cover plate were unlikely to cause problems with fatigue at a future date. A schematic of the overhead crane is shown in Figure 1. The regions where the two cracks were observed are highlighted and it is the crack at the northern end of the crane that we will consider in this article.

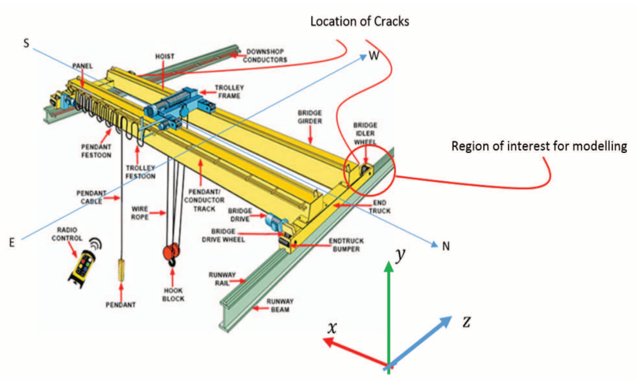


Figure 1: Schematic of the overhead crane highlighting the region of interest in this study

The crack in the region of interest emanated from a sharp corner where the bottom flange of the rectangular hollow section end truck member had been removed to allow the idler wheel to penetrate the member and reach the track on the runway beam – see Figure 2(a).

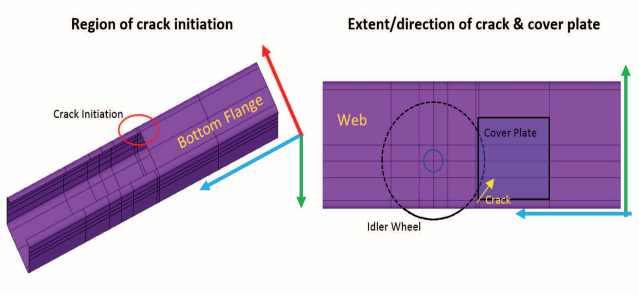


Figure 2: Crack initiation, direction of growth, extent and cover plate repair

At an inspection during my site visit it became apparent that the removal of the end portion of the bottom flange had been undertaken using some form of flame-cutting approach which left a rather poor finish of the sort that is fertile ground for early onset fatigue crack initiation. The cover plate used to repair the crack is shown in Figure 2(b). It is welded to the web of the end truck member around the four sides of the plate and the question posed by the insurers of the crane is how does this plate influence the stresses in the member. To answer this question some stress analysis is required both of the member alone and then with the cover plate welded on to it. But before presenting this, it is worth noting a brief history of the crane.

History of the Crane

The crane was built in the early 1990s for the previous owner of the building and was operated at about 90% of its Safe Working Load (SWL) capacity. Since about 2005 its present owner has operated the crane at only 30% of capacity. Whilst the number of lifts per day is currently only about 20, it is not known how often the crane was operated during its previous ownership. Of additional note is that the two cracks were only observed during the 2020 inspection which, it is understood, was a 'particularly thorough inspection'. So, it could be the case that the cracks pre-existed this year's inspection but were simply not detected. It is interesting to consider also that whilst there are eight sites where similar cracks could have developed, only two were detected.

Free Body Diagrams - Reaction Forces

Engineers tend to view structures in terms of free body diagrams. Such diagrams use arrows to show the loads applied to the structure together with the reactions at the supports which hold the structure in equilibrium. The applied forces come from the mass of the structure in a vertical gravitational acceleration field, i.e., force = mass x acceleration. The mass of the crane structure alone, m_d, leads to what is called the dead load, $m_d\, g$, whereas the mass of the trolley and payload, m_l, lead to the live load, $m_l\, g$, where g is the gravitational acceleration, 9.81m/s ^{2} .

The reactions due to dead and live load are shown in Figure 3. The live load can, of course, be positioned anywhere along the bridge beams, i.e., 0 ≤ x ≤ , however, as we are interested in capturing the worst case with the highest live load reaction at the northern end of the crane, the case where the trolley is adjacent to the northern end of the bridge beams, i.e., with the smallest value of possible, will be taken.

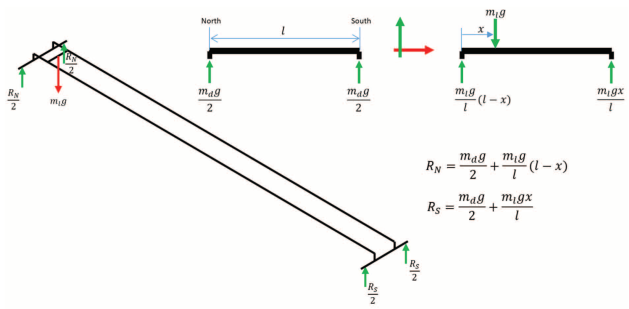


Figure 3: Free body diagram of the crane

Stress Resultants – Internal Forces/Moments

Thus, the reaction at the north-west crane wheel is half the total for the northern end trolley and the loading diagram shown in Figure 4 can be drawn. If we consider a cut through section z-z then the force and moment required to keep the section to the left of the cut in equilibrium are simply determined as shown in the right-hand part of the figure. Engineers tend to call these quantities 'stress resultants' and it is possible to draw diagrams of shear force and bending moment stress resultants showing how these vary in the region of interest.

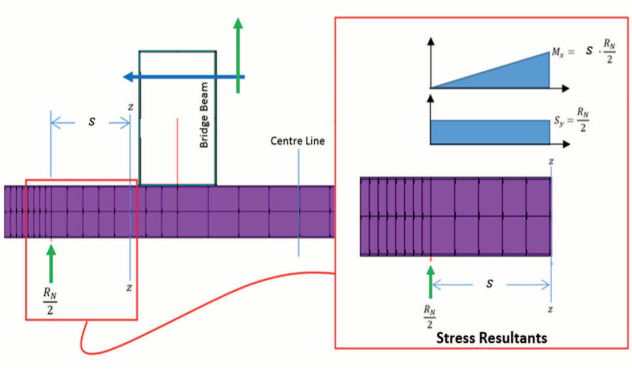


Figure 4: Stress resultants in region of interest

Stress Trajectories – Internal Load Paths

Once the stress resultants are known then using simple engineering theory for beam members, the stresses at any point across the depth of any section z-z may be determined. This theory tells us that the bending moment resultant produces a normal stress distribution that is linear through the depth of the member and a shear stress distribution which is parabolic. Whereas the shear distribution remains constant along the length of the region of interest, the linear normal stress distribution decreases (linearly) to zero at the point where the vertical reaction forces is applied, i.e., at the wheel. These stresses are shown in Figure 5 where principal stress trajectories have been used to represent the stresses. Principal stress trajectories are extremely useful to the practising engineer since they capture, in a single image, the load paths inside the member. They form a network of orthogonal lines and may be coloured according to the magnitude of the principal stress that they represent. Cracks tend to grow in a direction that is at 90 o to the maximum principal stress trajectories, i.e., parallel to the minimum principal stress trajectories, and the direction and extent of the crack shown in the figure are consistent with the actual crack observed in the crane.

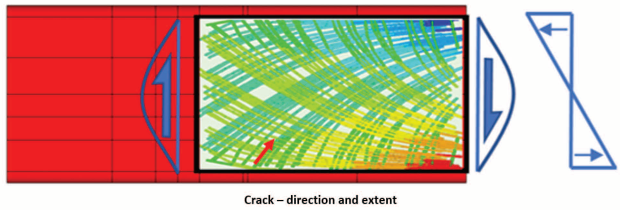


Figure 5: Stresses in region of interest

Although we have come a long way in determining the stresses in the members of the crane, this is about as far as we can go with hand calculations. In order to consider the influence of the cover plate on the stresses in the web of the end truck member, a different approach will be required. The reason for this is that the addition of the cover plates leads to plate thickness discontinuities which, in turn, will lead to stress discontinuities and concentrations which are nowadays tackled using finite element (FE) stress analysis. However, the work we have already done is not wasted, since the FE results may be verified, one of the essential parts of simulation governance, with the forces, stress resultants and point stresses already calculated by hand.

Finite Element Analysis

In a FE model, the structure is discretised using finite elements and there is a range of element types available to the engineer. In modelling the crane, I have chosen to idealise the majority of the structure using beam elements and then to idealise the region of interest, i.e., under and adjacent to the cover plate, using shell elements. The model is shown in Figure 6 where the cover plate is shown and the weld around the four sides of the cover plate is idealised using rigid-beam elements (shown as red lines).

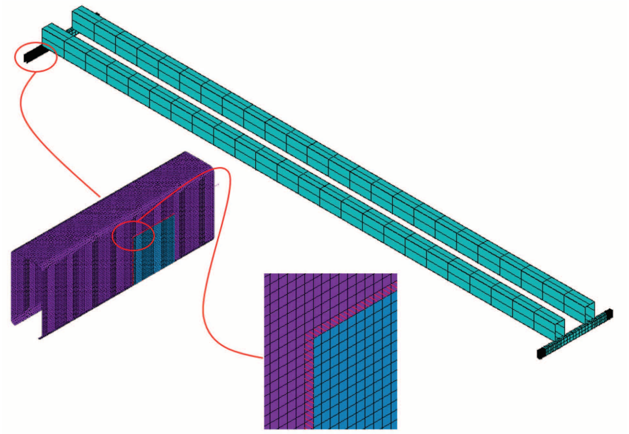


Figure 6: Beam/shell finite element model with removable cover plate

The contours of normal bending stress shown in Figure 7 agree extremely well with those calculated by hand. However, the stress distribution though now shows the local disturbances caused by the idealisation of the idler wheel axle as a point support and by the sharp corner of the flange cut-out.

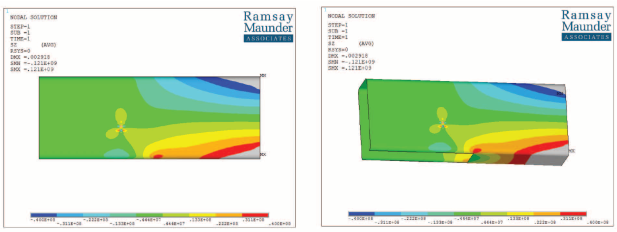


Figure 7: Contours of normal bending stress at full payload (without cover plate)

To model the influence of the cover plate correctly the analysis has to be split into two steps. In the first step the crane without the cover plate is analysed under dead load and then for the second step the cover plate is added and the live load applied. The contours of normal bending stress for the crane with the cover plate added are shown in Figure 8.

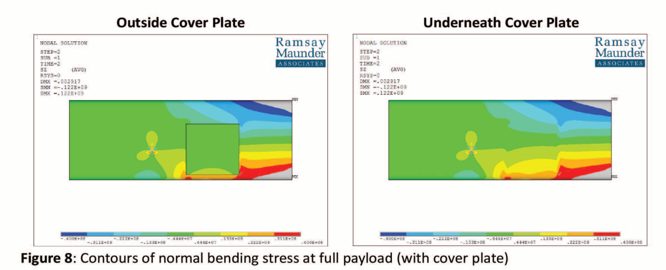


Figure 8: Contours of normal bending stress at full payload (with cover plate)

The insurers of the crane are essentially interested in the difference in the normal bending stress in the web of the end truck member due to the addition of the cover plate. This can be established by subtracting the stresses shown in Figure 7 from those shown in Figure 8 – see Figure 9.

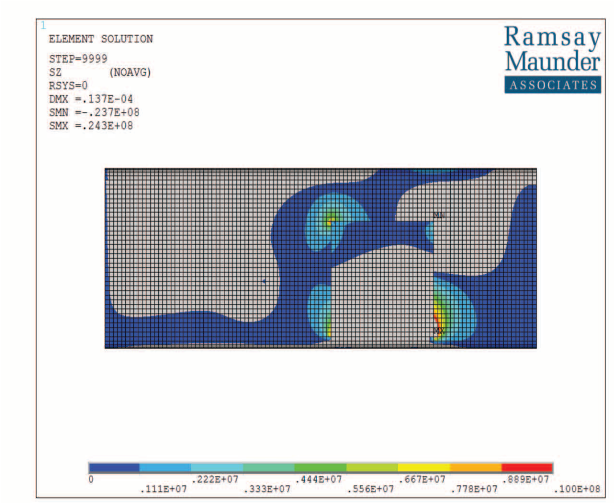


Figure 9: Contours of difference in normal bending stress for full payload

The contour levels in Figure 9 were chosen such that regions of negative stress, which indicate a reduction in stress due to the addition of the cover plate, are coloured grey. All other colours represent different ranges of increased stress and locate regions where the addition of the cover plate has impinged in a potentially harmful manner on the structural integrity of the member. It is noted that at the bottom left of the cover plate, where the original crack existed, the stresses have been reduced which might ameliorate crack growth should the crack reappear in the future. However, this has been at the expense of the top left corner and in particular the bottom right corner of the cover plate where the stress has been increased.

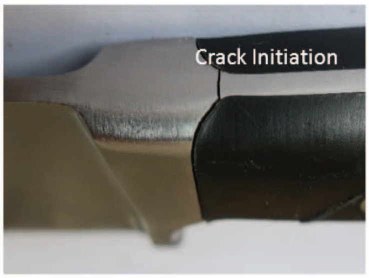
Fatigue Assessment of Crane

In designing a structure such as the crane, the engineer will need to ensure that the crane has sufficient stiffness so that under the service load the deflections are not unreasonable, and that the members have sufficient strength that even under an overload condition, the structure does not collapse. At least on an empirical basis, these conditions have been met. Had they not, the crane would have been scrapped a long time ago. There is one other potential mode of failure, known as fatigue failure, which the design engineer should also have considered during the design of the crane. This mode of failure only occurs when a structural member or machine component is subjected to tensile cyclic stresses. Most readers will have encountered fatigue failure during their life whether or not they recognised it as such, and two recent examples from the author's own experience are shown in Figure 10.

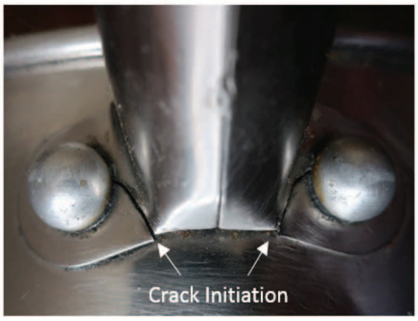
Figure 10: Recent fatigue failures from the author's kitchen (picture on next page)

The members of the crane are, mostly, subject to bending and will, therefore, see tensile stress regimes on either the top or bottom surfaces (flanges) of the member depending on whether the local mode of bending is hogging or sagging. For the region of interest in this case study, the mode of bending is

Figure 10:



The crack was probably initiated due to regular use of the knife to crush garlic which caused bending about the weak axis. The crack grew to the level seen at which point the knife was dropped and suffered a brittle fracture.



The cracks initiated at the sharp corners where the tabs for the two rivets used to join the handle to the pan were bent outwards from the pre-formed handle. The crack grew to the extend shown before the reduction in stiffness became noticeable. Had the pan continued to be used then it is likely that a ductile fracture would have been observed with the handle tearing from the pan.

sagging which leads to maximum tensile stresses occurring on the bottom face of the member – see Figures 7 and 8.

The realisation that failures could occur in metal components which were otherwise soundly designed based on a strength criterion was first noted in the early days of railway transportation with the rotating axles of railway vehicles which were observed to suddenly fail with stresses well below the yield stress for the material. This observation led to controlled experiments which subjected seemingly identical material specimens to the same cyclic stress regime. The results from these experiments, whilst containing some scatter, showed a relationship between the applied stress, *S*, and the number of cycles to failure ,*N*, Since this early work on fatigue, and despite an increased metallurgical understanding of the mechanics of the phenomenon, empirically derived *SN* curves remain the main approach to fatigue used in engineering design.

For the design of steel structures with welded connections, the Eurocodes provide a range of *SN* curves (EC9). Figure 11 shows the two extreme curves where the lower curve is for the type of welded connection or design detail producing the worst fatigue strength whereas the upper curve is for plain, unwelded material. Once the engineer selects the curve appropriate for his/her design detail then it may be used in a design mode, i.e., to find the design stress, for a given cyclic operating life of the structure, *N*, or in assessment mode where the stress is known, as for the crane, and the operating life needs to be determined. For the crane, the upper curve is appropriate for the end truck member away from any welds whereas, when the cover plate is welded onto the member, the lower curve becomes appropriate.

It will be noted that the *SN* curves in Figure 11 flatten out or become horizontal to the right of the figure. This indicates a very useful property of ferrous materials called the endurance limit. Stresses below the endurance limit for a particular design detail can be safely endured without the risk of fatigue failure.

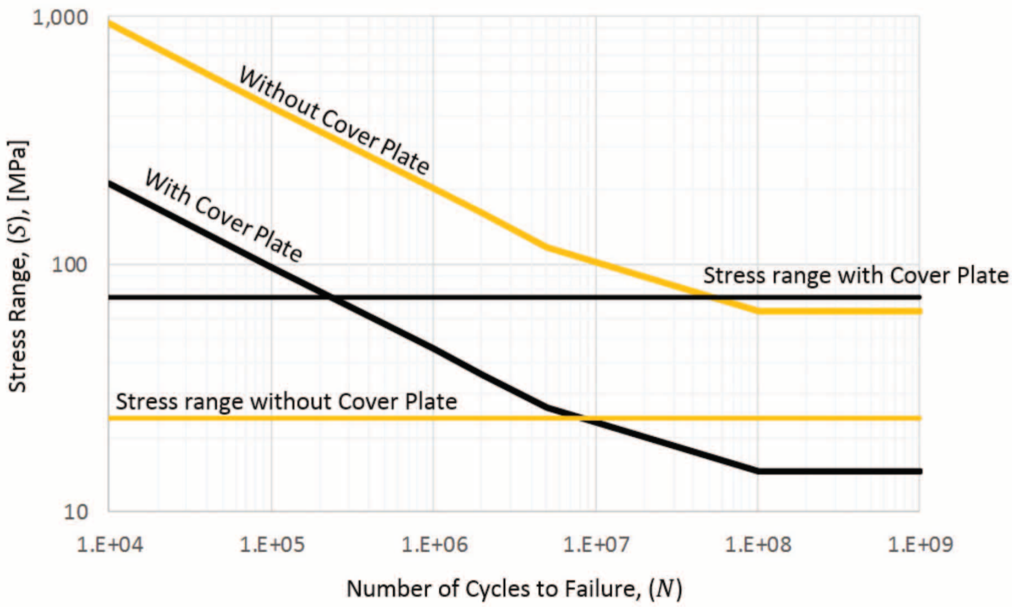


Figure 11: The lower and upper *SN* curves from Eurocode 9

The *SN* curves of EC9 use the stress range on the abscissa (y-axis). The stress range is simply the maximum stress in the operating cycle minus the minimum stress, i.e., the stress under full payload minus that under zero payload. For the case without the additional cover plate, analysis not shown in this paper gives the maximum and minimum stresses as 33MPa and 21MPa. This means that the stress range at the point of interest prior to adding the cover plate was 33 – 21 = 12MPa. When the cover plate is added to the member the stress at full payload is increased by 25MPa (Figure 9) giving a stress range of 33 + 25 – 21 = 37MPa. If we assume a dynamic amplification factor of two to account for the dynamic loads caused by acceleration and deceleration of the crane, then the stress ranges are doubled to 24MPa and 74MPa respectively.

It is seen from the annotated *SNS* curves of Figure 11 that whereas prior to the addition of the cover plate the stress range in that region was sufficiently low as to imbue an infinite fatigue life on the member, the addition of the cover plate leads to a finite fatigue life of just under 200,000 cycles.

In practice, under the current ownership, the crane is only loaded to 30% of its SWL and only undergoes about 20 lifts per day. However, on a conservative basis and taking the 200,000 cycles calculated for the full SWL cycle, the fatigue life of the crane is 200,000 / 20 / 365 = 27 years. The design life of the crane, when new, is not known although a reasonable life for an overhead crane might be 30 years. It has already served this period of time and so one might expect any further life to be a bonus.

Discussion

This article has presented a case study taken from one of the author's recent commercial projects. The first step was to establish the vertical reaction forces at the four wheels. With the reactions determined it is possible to plot stress resultant diagrams for shear force and bending moments. Had we been interested in the strength of the structure then these could have been compared with the capacity of the members to establish whether or not the structure was sufficiently strong. Since we were interested in fatigue, which requires knowledge of point stresses, we were able to use simple beam theory to establish how the stress resultants convert to stress distributions in the member of interest. For beam sections which have been modified as, for example, by having a cover plate welded onto the web, the step change in thickness will lead to stress concentrations. The correct magnitudes of these concentrations need to be established for a proper fatigue assessment but they require a more detailed analysis using finite elements. It is unlikely that the crane designer would, 30 years ago, have had access to FE in the design of the crane and any attempt to evaluate the stress concentrations would probably have been via published tables of such data. Inevitably such data does not generally cover all cases that the design engineer needs and, typically, not the particular one he/she requires.

As far as the commercial project on which this case study is based, RMA were able to present the necessary evidence to their client, the owner of the crane, and as required by the insurer showed that the addition of the cover plate did not unduly influence the future fatigue life of the structure. In this case study the fatigue life was quoted as 27 years. This was based on a payload of 90% of the SWL. In practice the maximum current loading is only 30% of the SWL and the corresponding fatigue life is in excess of 600 years!

It is the case that the large proportion of structural failures seen in structures or machines are fatigue failures. Some sources put this proportion as high as 90%. The reason for this is obvious. If there is an issue with stiffness, strength or stability then this will generally be picked up during commissioning of the structure or machine. The number of cycles required to initiate and grow a crack to its critical crack length when fracture will occur naturally takes time, so that any lack of fatigue resistance takes time to be detected. The time taken to develop fatigue induced fracture might be many years or it might be very early on in the structure's life. The author has been involved with legal cases where early onset fatigue cracks were not picked up during inspections and the resulting fracture of a member in a statically determinate lifting appliance, i.e., one with no structural redundancy, led to collapse of the structure and the loss of life, [2].

The author is always amazed, when being called to look at fatigue cracks in industrial machinery, at just how obvious it should have been to the designer that a fatigue crack would be initiated. The crane was no exception. The sharp corners left by removal of part of the bottom flange are obvious sites for stress concentration. Furthermore, not addressing the rough flame-cut edges simply exacerbates this issue by leaving probably multiple sites adjacent to the high stress at the corner where fatigue cracks would easily initiate. With additional effort at the design stage it is likely that a more suitable geometry could have been determined which would have alleviated the likelihood of fatigue initiation at this point. Even a healthy fillet radius would have probably done the trick but such a study would have required detailed analysis using FE analysis which was probably not available to the crane manufacturers some 30 years' ago.

The author recalls an occasion when he was privy to a discussion in the design office of a manufacturer of industrial gas turbines. Their previous blade design, whilst having great aerodynamic performance had suffered from early fatigue failures. Such failures are expensive since when one blade 'lets go', the resulting damage to the machine can be enormous and expensive to repair. The chief engineer was in the office giving a pep talk to his troops in preparation for the design of a new machine and concluded his talk with the statement '… and remember, NO SHARP CORNERS!!'.

In design against fatigue induced fracture, the engineer can adopt a fracture mechanics approach rather than a fatigue damage methodology of the form adopted in this article. In this approach the structure is assumed to have pre-existing cracks and the method is then used to establish whether the crack will grow and if so its critical length, i.e., the length at which fracture will occur. Such an analysis needs to be undertaken in conjunction with a member collapse analysis since it is possible that the reduced capacity of the member due to the presence of the crack might lead to the development of a plastic hinge prior to fracture.

Without a proper timeline for the crack in the crane it is impossible to tell when it started and how it grew, although it is clear by the absence of fracture of the member that it had not reached its critical length. The owners of the crane, by necessity to maintain production, on hearing that there was a crack in a critical member instigated the repair work. Had there been time at this stage an alternative approach would have been to commission a fracture mechanics assessment of the crack which might well have shown that it was dormant under the current loading regime and perfectly safe to live with.

The repairs made to the crane appear to have been undertaken on the 'belt & braces' principle and without any consideration of the unintended consequences of the repair that a more detailed analytical approach might have brought up. It is the case that the gouging out and welding up of the crack should have returned the fatigue resistance back to the 'as new' condition, [3]. The re-initiation of the crack could have been ameliorated and potentially stopped by addressing the poor geometry and surface finish at and adjacent to the sharp corner where part of the flange had been removed. It is also noted that the repair work was undertaken when the crane was unloaded. A more thoughtful approach might have been to repair it when fully loaded since by doing so a decent set of compressive residual stresses would have been gained for any future loads up to the fully loaded condition. And, finally, the whole area could have been treated with shot-peening to impart residual compressive stresses to the surface of the member to discourage future crack initiation. The purpose of the cover plate is unclear. It might, though, have been added as a gesture to increase the structural strength of the member should the crack reappear. The repairers would, I guess, be somewhat surprised to understand, as explained in this article, that by adding the cover plate they have reduced the fatigue resistance of the structure. As it happens, and it is guessed that this is purely by serendipity, the reduction in fatigue resistance is unlikely to result in crack initiation during the foreseeable remaining life of the crane.

Practical Conclusion

This case study has revealed a general lack of scientific rigour surrounding the inspection and repair of the crane. Apart from the fact that a crack was discovered in 2020, there is no timeline available and one is left having to guess the timeline or to substantiate it with associated structural analysis. A fracture mechanics assessment at the time the crack was discovered would have revealed whether or not it was still growing and how far away it was from being critical. Whilst the repair is likely to work, in the sense that a properly gouged out and welded up crack should recover the original fatigue resistance of the structure, it is unclear whether or not the root cause of the crack has been addressed. The addition of the cover plate, seemingly to add structural capacity to the member should a crack reappear, has had unintended consequences. Without the added cover plate the member had an infinite fatigue life but now, as a result of the addition of the welded cover plate only has a finite one. It is, seemingly, a matter of luck that the remaining fatigue life of the member is more than adequate to see the crane through the last part of its life.

Whilst I would not wish to cast aspersions on the inspector's competence, it is the case that they only discovered this crack during what was termed a 'particularly thorough' inspection. Why weren't all inspections thorough and what parts of the crane were checked for cracks during previous inspections?

Inspectors of critical lifting appliances such as overhead cranes or scissor lifts should be aware of the critical points within the structures they inspect. Whilst this knowledge can come from engineering experience, it was certainly obvious to most engineers that cracks would emanate from the stress concentration resulting from the removal of part of the bottom flange in the end truck member, this knowledge can only really come from the results of analysis. Based on the presumption that the manufacturer of the appliance has undertaken a formal analysis of the structure, it might be of benefit to the purchaser of the appliance to request a list of structural 'hot spots' which need to be inspected regularly and if this is not available, to commission one at their own expense.

It is worth noting also that whilst two cracks have now been detected and repaired, it seems unlikely to the author that similar cracks are not also present at the other side of the end truck member. The stress levels on either side of the member are, essentially, identical (Figure 7) and the sharp corner due to the partial flange removal is also present on both sides. It seems likely, therefore, that cracks will be present on these webs also but, because these sides of the member are close to the wall of the building and difficult to inspect let alone repair, these have been neglected or missed.

Had the crack not been detected in the 2020 inspection and had it grown to its critical length (assuming it still is growing) leading to the fracture of the end trolley member, and had the crane come crashing down on whoever was below it then the Health & Safety Executive (HSE) would have been brought in to inspect the situation and legal proceedings would, no doubt, have been initiated between some of the parties involved. The owners of the crane would probably defend themselves, arguing that they had employed reputable inspectors and repairers whilst the crane's insurers would no doubt attempt to avoid a pay-out by passing as much blame as they could reasonably get away with onto the inspectors and repairers. Likewise, the insurers for the inspectors and repairers might attempt to find fault in the way the crane was loaded and operated by the owner. At this juncture opposing sides might employ their own technical expert or the court might impose a joint party expert who will employ the same sort of techniques presented in this case study to assist the court in reaching a settlement. If the failure of the crane had led to fatalities or serious injury and there was suspicion of criminal behaviour, e.g., gross negligence or professional misconduct, then the consequences might be far more serious than the financial losses ….

Closure

The potential consequences of the structural failure of a crane or indeed any other lifting appliance are serious and should be taken as such by all involved. If the author were the owner of such a structure then he would make sure that he was aware of the potential failure points of the crane and would ensure that during inspection these points were monitored. He would also ensure that any repair was backed up, a priori, by suitable analysis of how the repair might impinge on the existing structure to make certain that there were no unintended consequences.

References

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Acknowledgements

The author is grateful to Dr Edward Maunder, a practising structural engineer and the Reverend Max Ramsay, an intelligent and interested layman, for their reading of and comments on this article.

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