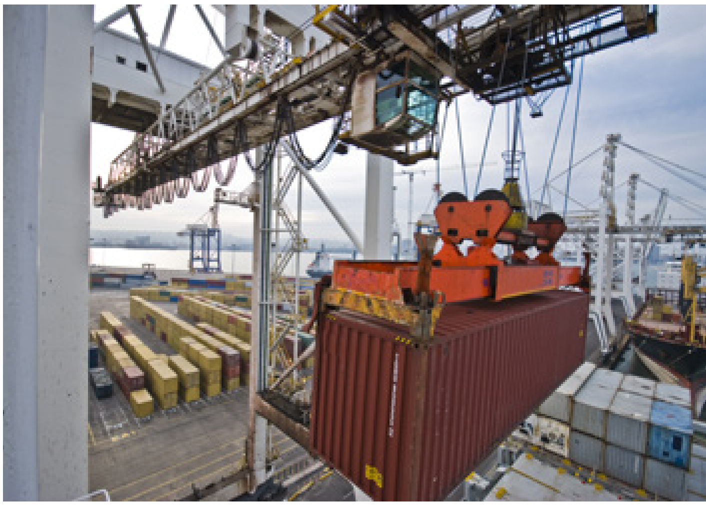
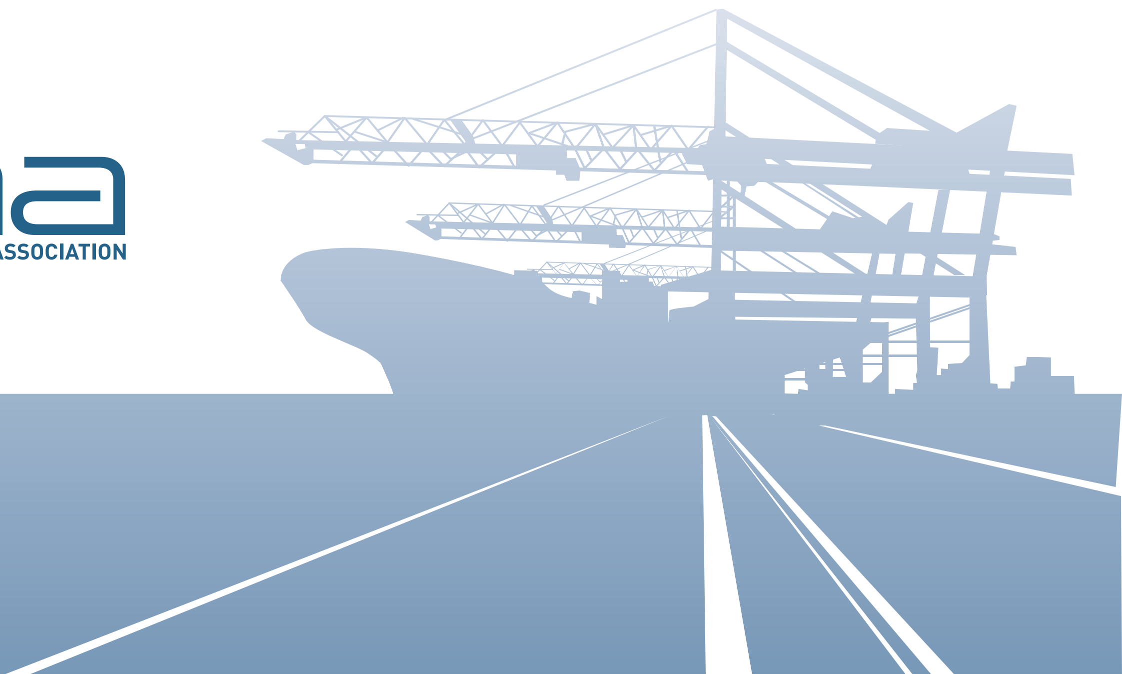
Practical Structural Examination of Container Handling Cranes in Ports and Terminals

A PEMA Information Paper



This Information Paper is intended to provide practical guidance about structural examination of ship-to-shore (STS), rail mounted gantry (RMG), and rubber tired gantry (RTG) cranes.

The goal is to increase understanding about the risk posed by fatigue failures, to explain the importance of structural examination, and to give practical guidance assisting terminal personnel to locate cracks by visual examination. We believe that some visual examination by non-specialists is better than none, but also that such examination does not replace a proper inspection program by a professional.



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PEMA would like to thank Liftech Consultants for kindly providing images.

INTRODUCTION

DOCUMENT PURPOSE

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OVERVIEW

This paper is about reducing the risk of fatigue failures on existing cranes and provides guidance about:

1. The main 'ingredients' of fatigue:
    a. Members loaded cyclically in tension
    b. Stress concentrations including those induced by welding
2. Fracture critical members on cranes–tension members under fluctuating loading whose failure would result in significant damage or loss, to which special attention must be given.

ABOUT THIS DOCUMENT

This document is one of a series of Information Papers developed by the Port Equipment Manufacturers Association (PEMA). The series is designed to inform those involved in port and terminal operations about the design and application of software, hardware, systems and other advanced technologies to help increase operational efficiency, improve safety and security, and drive environmental conservancy.

Further Information Papers, Surveys and Recommendations from PEMA and partner organisations can be downloaded free of charge in PDF format at: www.pema.org/publications

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The comments set out in this publication are not necessarily the views of PEMA or any member company.

The advice contained in this information paper does not carry any force of law, and is independent of the various local, national and international regulatory regimes on the safe design, manufacture, inspection and operation of cranes, which must be satisfied. Operators should also consult with their crane maker or an expert to identify critical inspection points and intervals, and should engage a professional to conduct these inspections.

FUTURE DEVELOPMENT

PEMA intends to develop the guidance in this paper further over time based on industry feedback, new technologies, and new examples of failures.

Additionally, it is important that further consideration be given to a practical and consistent approach to safety and risk across all port machinery design and use aspects, consistent with the European Machinery Directive and other standards.

For further information about this paper or to provide feedback, please contact the PEMA Secretariat at info@pema.org

1 | BACKGROUND

Steel structures subject to variable or repeated loading may fail in service at loads significantly below their static strength. This type of failure, resulting from the growth of cracks under variable loading, is known as fatigue. Nearly all failures in crane structural components are due to fatigue.

Welded steel structures always contain undetectable cracks, particularly at welded joints. Stress fluctuations beyond a small value cause the cracks to grow and eventually sudden failure by brittle fracture can result. So called "infant failures" can happen within the first few years of operation. But it may take 15 years or longer for dangerous cracks to be detectable.

According to data from the insurance firm TT Club, the third biggest source of equipment claims in ports worldwide is fatigue damage, making up about ten percent of the total. The two biggest sources of claims relate to operations and weather. Fatigue failures in port equipment, especially on ship-to-shore (STS) cranes, pose a significant human safety, operational, and economic risk. The risk of such failures can be reduced significantly by periodic structural inspections at key locations on the cranes.

In the worldwide fleet of about 5,000 STS cranes, each with thousands of cracks growing slowly, we estimate each year 150 cranes will develop a fatigue crack that can result in failure of a critical member. Most of these cracks will be discovered and repaired before member failure.

There is general awareness in the industry that fatigue failures of cranes sometimes result in dangerous and costly accidents. However, since the number of such failures is few, and information is typically not shared, awareness has not been sufficient to demand development of an industry wide standard for the structural examination of cranes. Some owners follow specific examination plans and others do not.

Typically, the owners who implement inspection plans do so from the experience of a dangerous failure.

The British Standard *BS 7121-2-9:2013, Code of practice for the safe use of cranes, Part 2-9 Inspection, maintenance and thorough examination—cargo handling and container cranes* provides guidance about maintenance and inspection of container handling cranes. Clause 6.3, *In-Service Inspections*, explains the fatigue problem and specifies an approach:

If left unattended, cracks can cause serious failure of the crane structure. The in-service inspection regime should include measures to detect cracks before the safety of the crane is affected. Therefore, in-service inspections should include a structural inspection of highly stressed areas of the crane.

If there are any indications of cracking…the crane should be taken out of use and a thorough examination should be carried out in accordance with Clause 8, with NDT if considered necessary by a competent person...

The period between inspections should be…between 1 week and 6 months.

TT Club, a port insurer, publishes a guide for maintenance of STS cranes that has similar wording. The International Labour Organization (ILO) Convention 152 also has similar language. However, the suggested inspection periods, while practical for visual inspection, are not applicable to in-depth inspection of structural components.

The recommended inspection periods for structural components and the testing requirements should be based on fracture mechanics and an acceptable risk approach. For most STS crane designs, typical inspection periods to maintain reasonable reliability are between 3 and 24 years. Regular visual inspection is useful, but cannot replace magnetic particle, dye penetrant, or ultrasonic in-depth inspection of components.

Picture 1.1: Critical elements at the landside crane apex that must be inspected periodically.

A common misunderstanding about fatigue failure is that after a crane has been reviewed by a crane certifier, been load tested, and received its annual inspection certificate, it has no chance of fatigue failure in the following year.

Certification and subjecting a crane to a test load demonstrates with reasonable assurance that the crane can carry the design load; but this indicates nothing about the presence and growth of fatigue cracks or the probability of fatigue failure.

Through discussion with PEMA members and a presentation at the 2014 PEMA annual meeting, it was agreed that a general paper on the subject of fatigue and practical structural examination *supplementing* British Standards and other related documents could be of value to the industry. We strongly recommend that this paper be read together with the applicable standards, such as the BS 7121-2, BS 7608:2014, *Guide to fatigue design and assessment of steel products* and other standards such as EN 1993-1-9: 2005, *Eurocode 3: Design of steel structures – Part 1-9: Fatigue*.

Members of the Working Group for this paper include specialized consultants, crane manufacturers, owners, and operators.

2 | CRITICAL FACTORS OF FATIGUE FAILURE

The risk of a fatigue failure is the product of the probability and the consequence of the failure. There are three critical factors: two relate to probability and one to the consequences of that failure.

Two primary factors control the probability of fatigue fracture:

1. The number and range of tension stress cycles at a particular point in a structural member determine the probability of crack growth, also called fatigue damage. More stress cycles and greater tension stress range in each cycle increase the damage and the probability of failure. For many members on cranes the loading varies directly in relation to the magnitude and position of the moving load.
2. Stress concentrations, which increase the local stress range, increase the probability of crack growth. Stress concentrations are locations on a member where, due to discontinuities in geometry, local stresses are much larger than the average across the section. Stress concentrations are typically found at discontinuities such as connections, especially at welds.

Lesser factors affecting fatigue performance include residual stresses from fabrication, material properties, loading rate, and temperature.

Picture 2.1: Crack in FCM at lower end of single upper diagonal pipe.

The consequence of failure is the third critical factor affecting risk. If failure of a structural member can result in dropping the load, collapse of the crane, or other dangerous instability, the consequence is significant. If such a member, or a portion of it, is loaded in tension the member is referred to as a fracture critical member or FCM. Inherent in this definition is that an FCM does not have a viable redundant load path.

The highest risk crane structural components are the FCMs experiencing severe fatigue damage, in particular at the locations with significant stress concentrations.

After a crane is built, mitigating fatigue risk is typically done by finding the fatigue cracks and repairing them before a member breaks (improvements of poor fatigue details is possible, but rarely done). This paper provides guidance to help find cracks through understanding of these three critical factors.

2.1 INSPECTION METHODS AND INTERVALS

Although the rate of fatigue crack growth is controlled by many highly variable factors, the probability of failure of a particular member, at some point in its life, can be approximated using data from testing of actual samples with similar fatigue details, calculations of the stress range the member experiences, and estimates of the number of load cycles.

Pictures 2.2 and 2.3: Fatigue fractures of diagonal members on machinery trolleys.

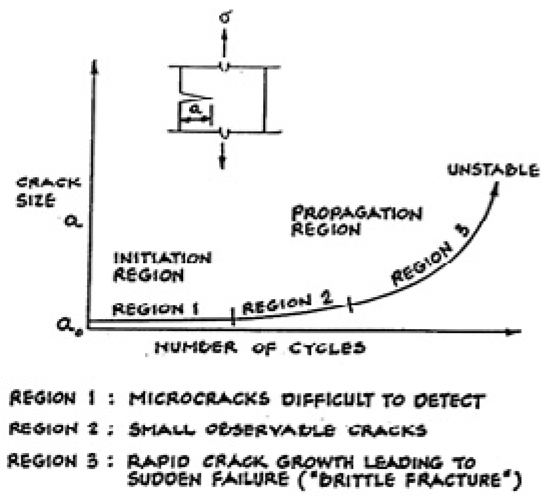
The best way to reduce the probability of a dangerous failure is to make thorough inspections of FCMs at intervals calculated based on the probable rate of crack growth. By inspections we mean visual and other non-destructive methods including ultrasonic, dye-penetrant, and magnetic particle examination by a certified weld inspector. Such inspections can be timed to maintain a consistent structural reliability.

Ideally, the crane maker provides the user with a structural maintenance program that specifies inspection locations, methods and intervals.

If an inspection program is not available, it can be worthwhile to make regular visual inspections at the critical locations on the crane. We note, however, that the usefulness of visual inspections alone to detect dangerous cracks is limited:

1. Visual inspection will not detect flaws inside the material, as can be detected by ultrasonic examination.
2. Surface cracks may not become visible until they have grown to a fracture critical size.

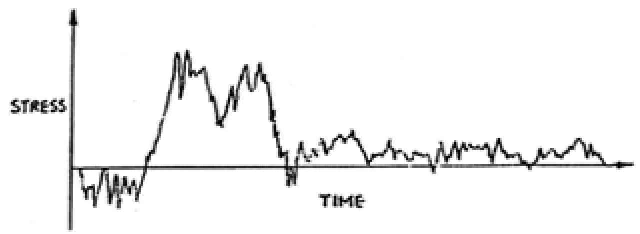
Picture 2.4 shows phases of crack growth. Cracks can be detected in Region 2 and repaired. In Region 3 fracture is imminent. For critical members, inspection intervals can be determined based on the number of cycles required to go from Region 2 to Region 3.



Picture 2.4: Phases of crack growth.

2.2 NUMBER AND RANGE OF STRESS CYCLES

On any crane the moving of the load by the trolley and the variation between loaded and unloaded states creates fluctuating stresses in the structure. On RMG cranes significant fatigue damage can also be induced by the gantry motion. Loads from acceleration and wind also create fluctuating loads, but the moving load is typically the most significant.



Picture 2.5: Typical fluctuating stress level at one point on a working crane. Each peak and trough is one cycle.

The number of cycles of this fluctuating stress and the stress range, particularly in the tension range where the material is pulled apart, are the most important factors in evaluating the potential for fatigue cracking.

Higher fatigue damage means there is greater probability of cracking and reliability is lower.

The greater the stress range—the difference between the minimum and maximum stress—the greater the rate of crack growth per cycle of load. The influence of the stress range on reliability is typically cubed.

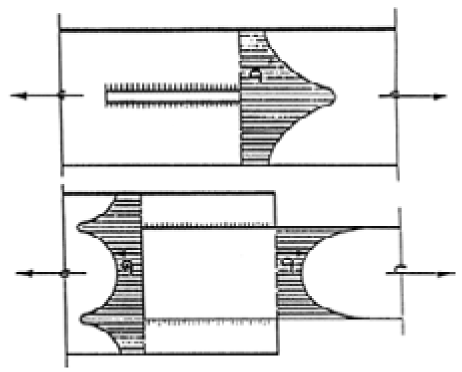
The more cycles, the more the cracks will grow. The influence of the number of cycles on reliability is linear.

2.3 STRESS CONCENTRATIONS

There are discontinuities in all steel structures, especially at welded joints. When the structure is loaded repeatedly in tension, the cracks grow perpendicular to the stress direction.

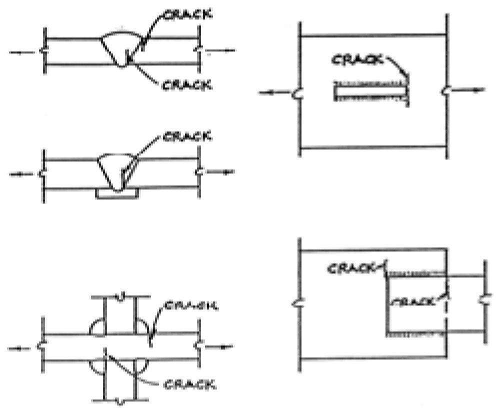
The rate of growth partially depends on the stress level. Stress concentrations cause higher levels of local stress and accelerate crack growth.

Attachments to plates and changes in geometry are discontinuities that cause stress concentrations, particularly at the welds. The cracks can occur anywhere in steel, but they usually occur at welded connections.



Picture 2.6: Examples of welded attachments and the stress concentrations that arise: At the top, a bar is welded perpendicular to the plate. At the bottom, a plate is lapped over another plate.

Picture 2.7 shows typical locations of crack initiation and subsequent crack growth due to stress concentrations that multiply the stress range. The cracks typically grow from tiny notches created by the heating and subsequent shrinkage of the welding process.



Picture 2.7: Examples of crack initiation and growth due to stress concentrations.

Picture 2.8: Looking down on a forestay connection plate that failed in fatigue.

2.4 WHERE CRACKS GROW - A DISCUSSION FOR CRANE STRUCTURES

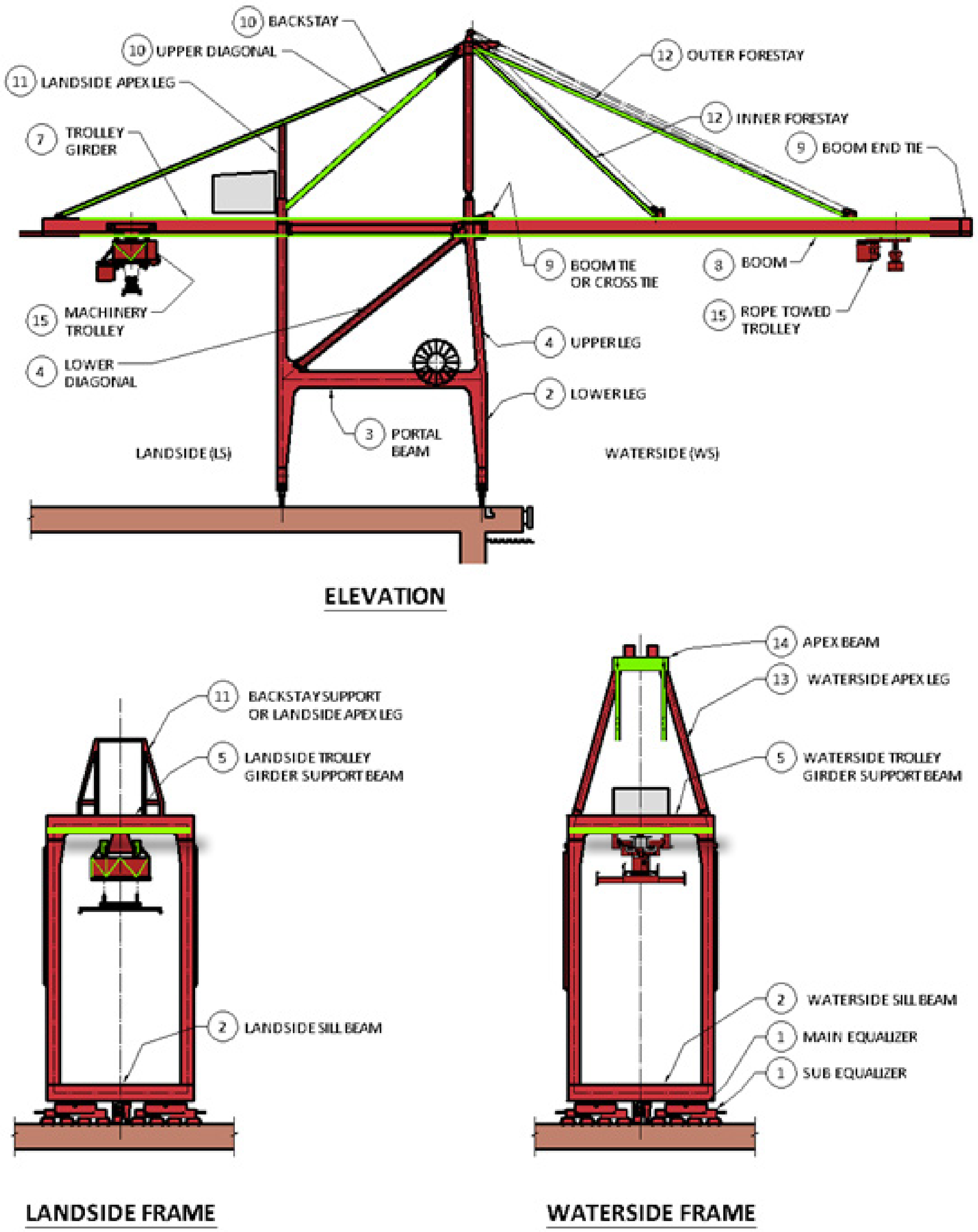
For cracks to grow from fatigue loading there must be a cyclic tension stress at a particular location. Where a geometric discontinuity is present there will be a stress concentration, a greater stress range, and a higher probability that fatigue cracks will occur.

When looking for dangerous fatigue cracks on a crane, in particular:

1. Look for FCMs
2. On the FCMS look for the regions that experience a significant fatigue damage
3. Within these regions look at changes in section and at geometric discontinuities, and particularly at the welds in these areas.

Typical cracking locations in main tension members, or portions of members, are at the ends of connection plates, at attachments and wraparound welds, and at changes in cross section.

3 | PRACTICAL STRUCTURAL EXAMINATION



Picture 3.1: STS crane member terms and FCMs. The green lines indicate FCMs, typically with high levels of cyclic tension that should be inspected at regular intervals. The numbering is consistent with the following sections.

The cyclic stresses in crane members are caused primarily by the trolley hoisting the load and moving with it. To understand which elements go in tension as a result of this movement, study how the forces flow from the trolley into the structure.

It should be clear that when the trolley is on the boom, which is hinged at the base, the forestays hold up the boom and must be in tension. Then follow the load.

What holds the forestays at the apex? This must be the upper diagonal that carries the horizontal component of the forestay load from the apex down into the trolley girder. Since the forestay pulls one way, the upper diagonal must pull the other way by an equal amount and also be in tension.

Since they are angled downward, both these loads have a vertical component at the top, which is resisted by the apex legs, in compression.

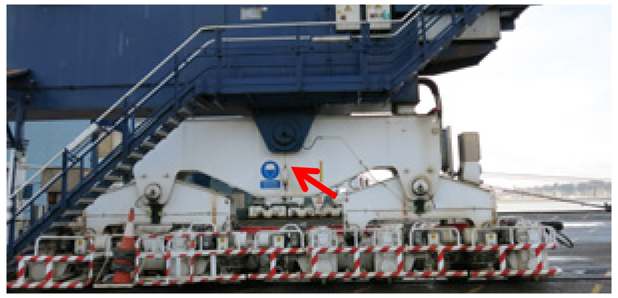
The forestays and upper diagonals are critical fatigue members, loaded cyclically in tension, that must be inspected for cracks on a regular basis—at both ends and at discontinuities along their length.

The following discussion covers all crane members generally, working from the bottom up. We include some discussion of the loads in the main members for the layman. We pay special attention to identifying the FCMs but note that any cracks on the cranes can eventually be dangerous and that any visible cracks can lead to questions about crane safety that may affect operations.

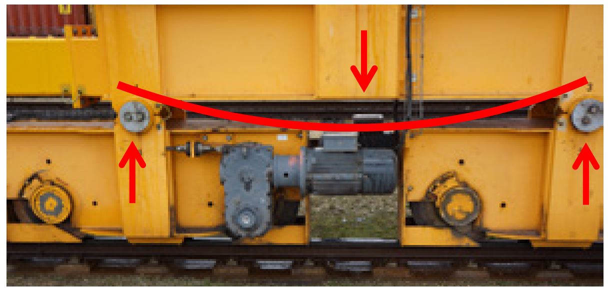
Note that many cracks in girders start at internal stiffening elements and propagate from there into the main plates.

Failure of non-fracture critical members (NFCMs) can result in overloading of other components, including critical members.

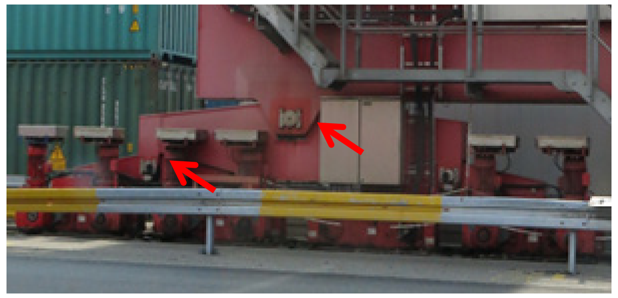
3.1 EQUALIZERS AND TRUCKS - NFCM OR FCM, DEPENDING ON TYPE AND LAYOUT



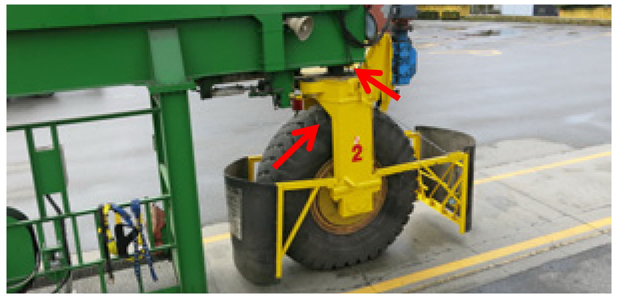
Picture 3.2: STS crane gantry system with 4 of 8 wheels driven per corner.



Picture 3.3: RMG crane driven at all 4 wheels.



Picture 3.4: RTG crane with 1 wheel per corner.



Picture 3.5: RMG crane driven at 5 of 6 wheels.

The equalizer beams are loaded by the weight of the structure at all times. The trolley moving load adds a cyclic stress component that is typically low and not a source of significant crack development. On RMG cranes, as shown in Pictures 3.3 and 3.4 above, the lateral driving forces from the gantry motors can be a source of significant fatigue damage. The ear plates indicated by the arrows at Picture 3.4 can be critical elements. RTG cranes can also experience fatigue cracks in the areas indicated in Picture 3.5.

On some large STS cranes it has been observed that the significant flexing of the structure combined with local geometric constraints result in high local stresses and premature crack development, particularly in the area of the web below the main equalizer pins indicated by the arrow in Picture 3.2.

This example of deformation combined with locally rigid geometry resulting in cracks is a recurring problem on modern container handling cranes. We will return to this topic when discussing forestay connection plates on the boom and the underhung machinery-on-trolley (MOT) type of trolley design.

Typical locations to look for cracks at the equalizer beams and trucks are at changes in geometry near the bottom flange and in highly stressed areas such as the web plate in the equalizer beams, below the pin. For lateral loads on RMGs, the area around the ear plates at the pinned connections is important, indicated by the arrows in Picture 3.4. On RTG cranes gantry loads often cause fatigue cracks around the yoke guiding wheel assembly. The vertical RTG yoke pin, indicated by the upper arrow in Picture 3.5, had a horizontal fatigue crack that was regularly repaired by maintenance.

The main loads and the curvature of the beam are marked on Picture 3.3. With the curvature shown, the lower flange of the beam is in tension.

On STS cranes, failure of the bottom tension flange of the main equalizer would cause severe damage to the crane, but is unlikely to result in collapse. For this reason, we do not consider the equalizers and trucks fracture critical members. On RMG and RTG cranes, these areas can be fracture critical.

3.2 SILL BEAM AND LOWER LEGS – NFCM

Picture 3.6: Sill beam with legs centered on equalizer pins.

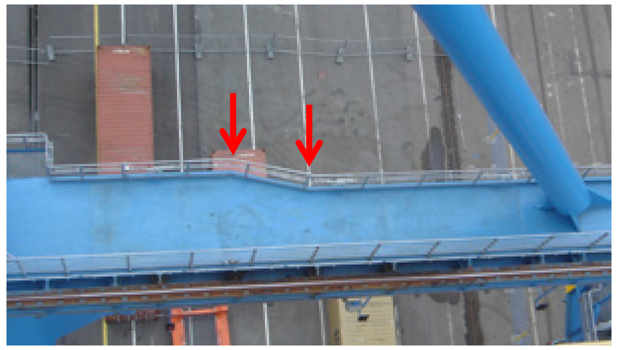
Picture 3.7: Sill beam with legs cantilevered beyond equalizer pins.

Of the two types of sill beam design shown above, only the type shown in Picture 3.7 results in cyclic tension at the top flange due to the moving load. With proper detailing, fatigue of the sill beams is not a major issue—the design is normally controlled by storm wind loads.

The legs are typically in compression under all operating load conditions. The bending stresses from normal operating lateral loads on STS cranes do not result in significant cycles of stress. Tensile stresses usually only occur due to residual stresses from fabrication. Typically, fatigue failure is not a significant issue for crane legs.

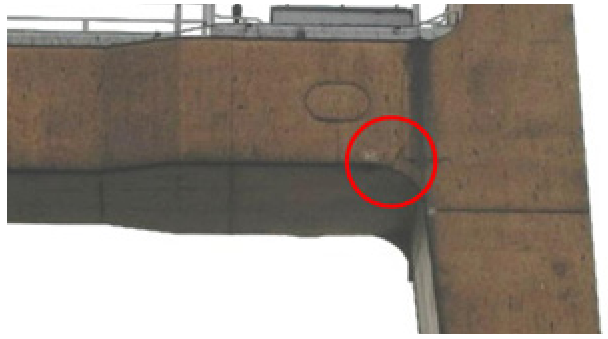
The legs and sill beams are not considered to be fracture critical members.

3.3 PORTAL BEAMS - NFCM

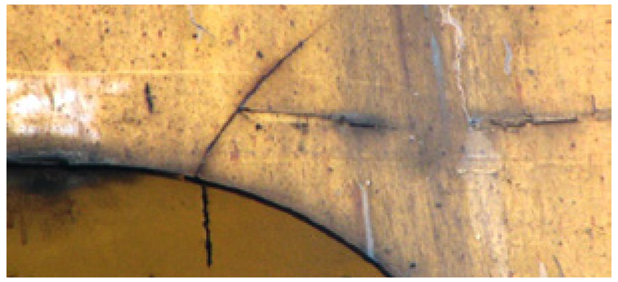


Picture 3.8: Portal beams with tapered end sections. The arrows indicate the transition points. The change in direction of the load in the web plates means there can be a significant cyclic tension load in the internal diaphragms.

Picture 3.9: A crack in the inside diaphragm at a transition in the portal beam.



Picture 3.10: Another type of portal beam crack.



Picture 3.11: The same crack seen up close.

Picture 3.12: Sill beam, lower legs, and portal beam. Note landside lower legs are pinned at the portal. In this case, all horizontal loads are taken by the waterside legs, on the left.

The portal beams and lower legs transfer loads in the trolley travel direction to the ground. Typically, well designed portal beams, with a constant cross section, have not experienced significant fatigue damage. On some large cranes with tapered portal beams cracks have been found regularly at the portal beams and legs at member transition points. The critical locations are indicated in Pictures 3.9 to 3.11. The cracks are due to crane deflections in the trolley direction during operation.

Historically, portal beams have had few fatigue problems because the mass of trolley and load, and trolley accelerations were low. Modern cranes are larger, have heavier trolleys, lift heavier loads, and have higher operating speeds and accelerations, resulting in greater forces and deflections in the trolley travel direction.

The portal beams are not fracture critical members but substantial cracks can change the crane behavior and must be addressed promptly.

3.4 LOWER DIAGONALS AND UPPER LEGS

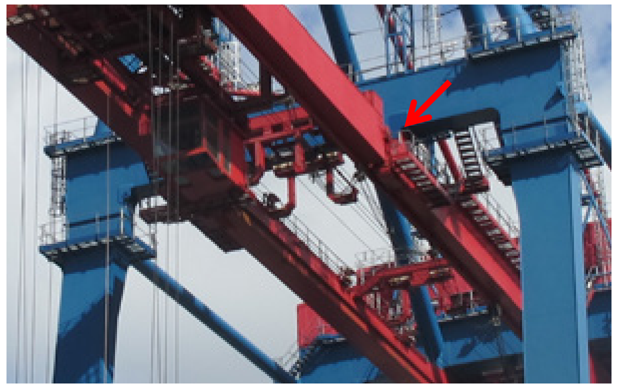
Pictures 3.13, 3.14, 3.15 and 3.16: Different arrangements of lower diagonals.

There are many possible arrangements, but the function of each is the same. The diagonal bracing at the upper leg level is provided to give the cranes stiffness in the trolley travel direction, transferring lateral loads from the trolley girder to the portal beam level. The upper legs are primarily compression members. Fatigue cracking is typically not a significant issue here and the members are not fracture critical.

If there are cracks, they are likely to be at the end connections of the pipe members.

3.5 TROLLEY GIRDER SUPPORT BEAMS (TGSB) AND HANGER CONNECTIONS - FCM

Picture 3.17: Welded TGSB to girder connection on twin girder crane with curved transition details to minimize stress concentration.



Picture 3.18: WS TGSB of twin girder crane. The arrow points to a detail similar to that shown in 3.17.

Picture 3.19: WS TGSB with pinned connection to plate girder boom.

Picture 3.20: WS TGSB of a monogirder crane with pinned connection.

Picture 3.21: Welded LS TGSB connection to monogirder boom. Notice the large radii at the transition.

Picture 3.22: LS TGSB of a truss boom crane, in this case without radii at the points of transition.

The trolley girder support beams, which carry the entire weight of the trolley girder and much of the boom weight, are subject to bending stresses with every trolley operating cycle. At the bottom flanges, in the vicinity of the connections to the trolley girder, there is a combination of stress concentration inducing weld details and high cyclic tensile stresses in bending from the beam and in tension from the hanger. An example is shown in Picture 3.17.

The pictures show examples of different types of connections to the trolley girder. The connection is generally called a "hanger connection." Regardless of the connection, these beams, at landside (LS) and waterside (WS), are always fracture critical members and the points of highest stress are around the connection of the beam to the hanger and trolley girder.

The hanger plates and their end connections, pinned or welded, are likely locations of fatigue cracks, particularly at the TGSB. The pictures show transition curves incorporated in some designs to reduce stress concentrations. The TGSB bottom flange and the hanger connection are some of the most important points to look at on a crane when looking for fatigue cracks.

3.6 TROLLEY GIRDER SUPPORT BEAM STRUTS

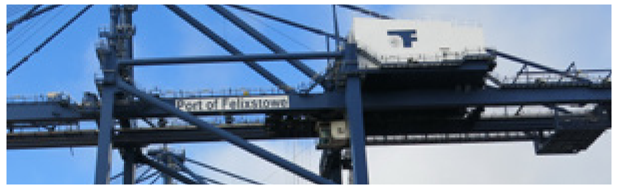
Bracing members in the plane of the trolley girder support beams provide rigidity against twisting when the crane is subjected to torsional loads about a vertical axis through the crane. These members are not fracture critical.

Pictures 3.23 and 3.24: Various bracing members in the plane of the TGSB.

The stiffening member shown under the trolley girder support beam in Pictures 3.19 to 3.22 increases rigidity against lateral loads in the gantry direction. The points where this member connects to the bottom flange of the TGSB have stress concentrations and should be specifically inspected.

3.7 TROLLEY GIRDER - FCM

Picture 3.25: Trolley monogirder.



Picture 3.26: Trolley twin girder.

Picture 3.27: Truss type trolley girder.

The trolley girder is subjected to a significant cyclic stress range from the trolley load. Depending on the location along the trolley girder, the top flange or the bottom flange may be in tension. The discussion about the boom below applies equally to the trolley girders.

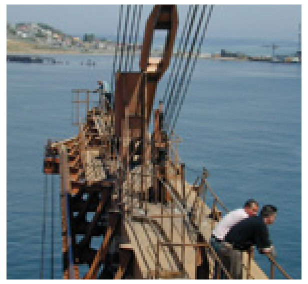
Picture 3.27 shows a crane with a truss type trolley girder and boom. A truss structure can in some cases be lighter than a continuous girder and therefore has certain advantages in the crane design.

The disadvantage of the truss design is in the difficulty of correct fabrication and the many members and critical weld connections that reduce the reliability of the structure.

Primary members of the truss experience a significant stress range from every move and many have complicated end details with stress concentrations. Truss structures are used successfully on cranes but the owner must be aware of the inspection requirements. The inspection effort for truss type trolley girder and boom structures is significantly greater than for box section structures.

3.8 BOOM - FCM

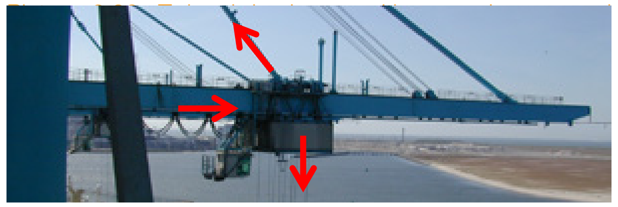
Picture 3.28: Truss boom.



Picture 3.29: Monogirder boom with trolley running at bottom.

Picture 3.30: Twin girder booms with minimal cross bracing.

Picture 3.31: Twin girder boom with cross beams and diagonal bracing.



Picture 3.32: Monogirder boom with underhung trolley. Arrows show the load from the trolley and the resisting tension load in the forestay. There is also a smaller horizontal load component of compression in the boom.

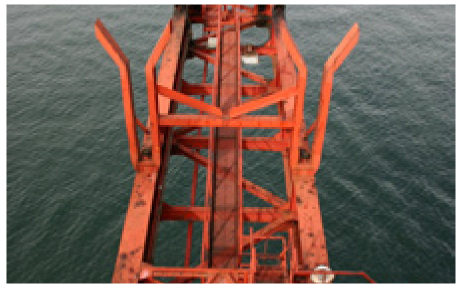
Typically, the lower flange of a boom box girder, or lower chord of a truss girder, is a tension element and an FCM. Due to the continuity of the boom between the forestay supports, there may also be tension regions at the top flange. On the cantilever section, beyond the outer forestay, the upper flange, or chord, of the boom is always in tension and is an FCM.

The design of the boom (and trolley girder) is typically controlled by fatigue. Cracks are most probable at areas of high stress concentration in the areas subject to cyclic tensile stresses. Failure of a tension flange, or chord, on the boom girder can result in failure of the entire member.

Many cracks have been found in the boom hinge area and at the inner boom cross tie on twin girder cranes. Another typical location, especially on machinery trolley cranes, is in the web under the trolley rail. As discussed in the section about the forestays below, the forestay connections to the boom are fracture critical and must be given special attention. The boom hoisting sheave connections are also fracture critical, but see relatively few cycles of loading.

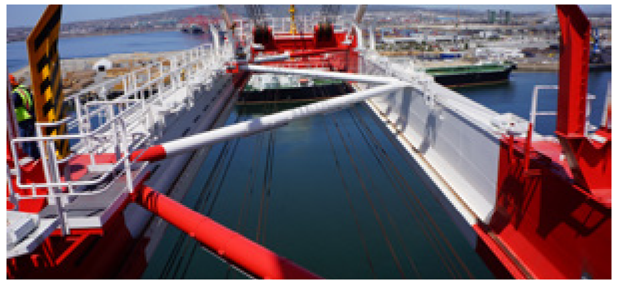
On the boom and trolley girder particular attention must be paid to attachments. Often, cracks are found at walkway supports and attachments to support electrical components. The welds of these ancillary structures create stress concentrations that can result in cracking in the main structure, or a crack can propagate from the ancillary structure into the main structure.

3.9 BOOM AND TROLLEY GIRDER TIE BEAMS AND DIAGONAL BRACING

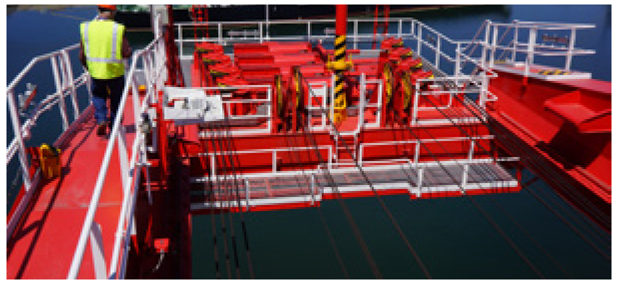


Picture 3.33: Twin plate girder boom with diagonal bracing and various tie beams.

Picture 3.34: Twin girder boom with tie beam.



Picture 3.35: Twin girder boom with typical diagonal bracing for lateral stiffness.



Picture 3.36: Twin girder boom end tie for dual hoist crane. The structures supporting the ropes are fracture critical.

Any additional members on the boom or trolley girder structures, such as the bracing members in Picture 3.33, are potential sources of cracks, particularly at their end connections. These cracks can propagate into the main structure.

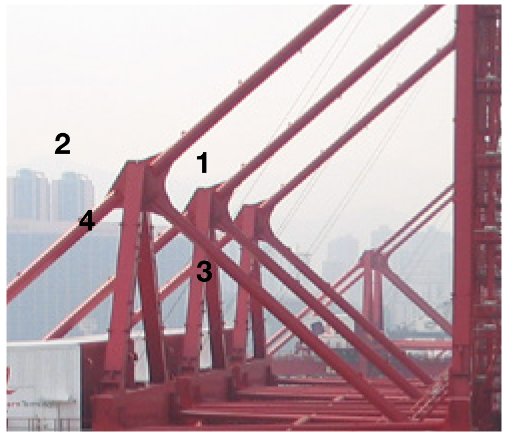
With a twin girder boom, as shown in Picture 3.34, the main members rotate slightly when the moving load passes, which bends the tie beams. Therefore, these members experience a fluctuating load and may develop cracks.

The end ties of twin girder booms and trolley girders are also subject to large and fluctuating rope loads.

3.10 UPPER DIAGONAL AND BACKSTAYS - FCM

The upper diagonals and their end connections are critical because if a member fails, the apex legs go over forward and the boom drops. The forestays are equally critical, but have historically experienced fewer problems.

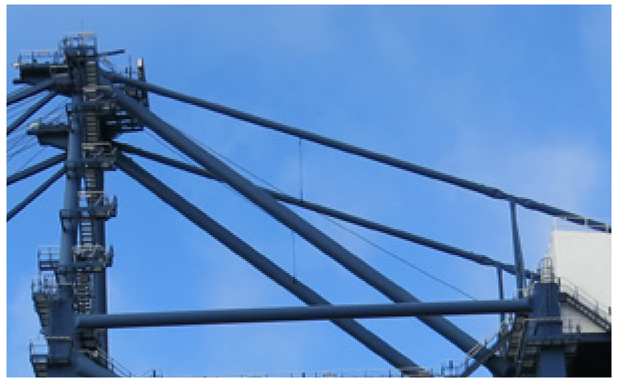
Several catastrophic and many near failures have shown that the upper diagonals are significant sources of dangerous fatigue failures. The end connections of these members in particular should be regularly examined.



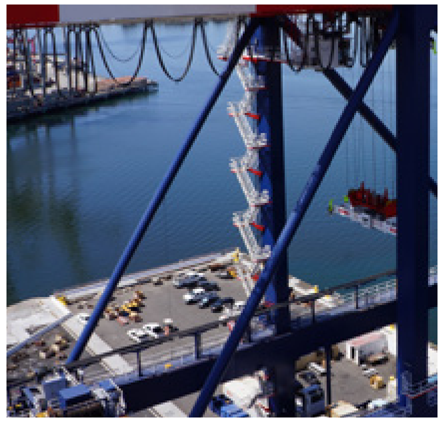
Picture 3.37: Typical arrangement for monogirder cranes - upper diagonal and backstay combined in one member. For member action, see discussion under LS Apex Legs.

Picture 3.38: Different design but same arrangement as Picture 3.37.

Picture 3.39: Upper diagonal connecting to forestay at the top trolley girder at bottom.



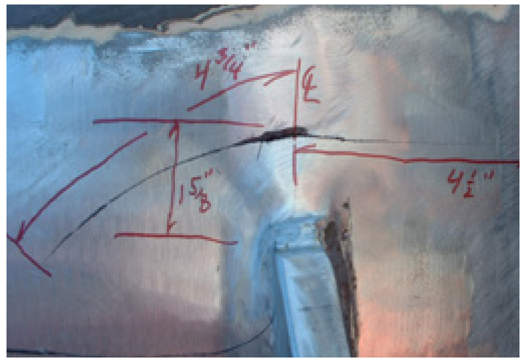
Picture 3.40: Typical arrangement for twin girder crane, backstays above the upper diagonals.



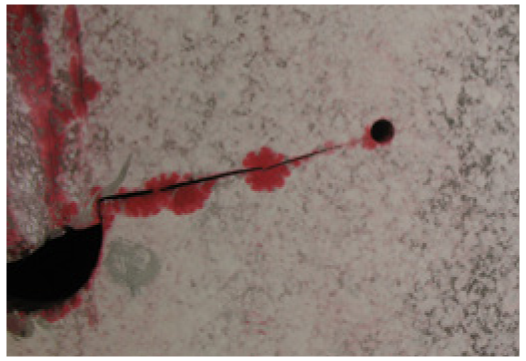
Picture 3.41: Lower backstay on a twin trolley crane.

Picture 3.42: Crossing tension members, landside and waterside upper diagonals.

Picture 2.1 is an example of a crack that could have fractured the upper diagonal. Pictures 3.43 and 3.44 show other examples.



Picture 3.43: Dangerous cracks in an upper diagonal member. The member can fracture at any time.



Picture 3.44: A crack propagating from a weld at the end of a connection plate, highlighted with dye. The hole at the right was drilled to temporarily stop the crack.

As the photos demonstrate, typical crack locations are at the end connections, in particular near the ends of connection plates and around stress relief holes.

It is important that the crane design incorporates permanent access for inspection of each end of these members and their end connections. Pictures 3.45, 3.46 and 3.47 below show examples where no inspection access is provided.

3.11 APEX LEGS, LANDSIDE - FCM

Pictures 3.45, 3.46 & 3.47: Fracture critical connections of the upper diagonals at the landside apex legs.

Pictures 3.45, 3.46 and 3.47 show fracture critical connections of the upper diagonals at the landside apex legs. Picture 3.46 shows a mono-girder design similar to that shown in Picture 3.38. Picture 3.47 shows a twin girder design similar to that shown in Picture 3.40. The upper member (1) in each image is the upper diagonal that carries the tension loading from the forestays.

The lower member (2) that extends as a continuation of the upper diagonal is a tension support for the cantilever backreach of the trolley girder. The lower diagonal member (3) is a compression strut when member (1) is loaded in tension, but a tension member when member (2), the backstay, is loaded in tension.

All of these members, and their end connections, are fracture critical. Depending on the position of the trolley and boom, any of the four members shown in 3.45, and 3.46 may be in tension or compression.

Note that the upper diagonal in 3.47 is a separate member and is not part of the connection here. Failure in this frame is not fracture critical, while failure of the pinned backstay members above the bracing frame are fracture critical, as this may result in failure of the trolley girder.

See the further discussion of the similar action of members at the WS apex beam below.

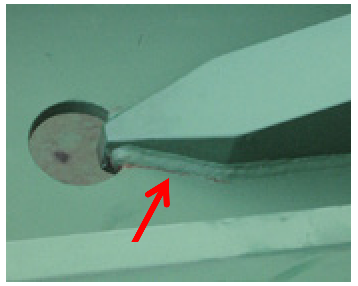
3.12 FORESTAYS - FCM

The forestays carry, in tension, the full load of the boom and, when the trolley is on the boom, the trolley and lifted load. Forestays experience one or more load cycles from each operating cycle of the trolley.

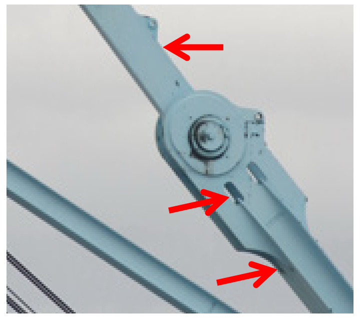
The failure of a forestay can lead to dropping the boom and the load—depending on the number of forestays and other factors. Therefore, the forestays are fracture critical members and must be carefully designed to minimize stress concentrations and crack inducing weld details. The end connections of each forestay link are typical crack locations.

Picture 3.48: A geometrical discontinuity in the forestay. This area will have severe stress concentrations.

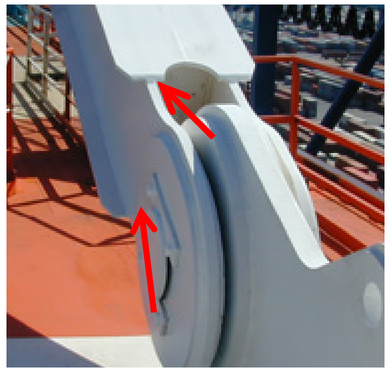
Picture 3.49: Forestays of three monogirder cranes. Sagging and straightening of the stays, due to loading and unloading the boom, results in stays bouncing up and down, which increases fatigue cycles of load.



Picture 3.50: A crack in the weld at the end of a forestay connection plate -in spite of stress relief hole. The relief hole reduces the stress concentration but does not eliminate it.



Picture 3.51: Upper arrow indicates stress riser at lifting lug on link. Middle arrow shows stress relief holes at end of stay flanges. Lower arrow indicates typical crack location for connection plates, particularly on the bottom side.



Picture 3.52: Wrap-around detail on a forestay resulting in a high stress concentration. Wrap around details, where the corner of the plate is welded from the top and the side, result in an extreme stress concentration and shortened fatigue life.

Picture 3.53: A crack at a forestay end connection plate.

Picture 3.54: A crack at the boss weld on the boom forestay connection plate.

Picture 3.55: A crack indication at the end of a lifting lug on an intermediate forestay link plate.

Picture 3.50 shows a crack at the end of a connection plate on the forestay, in spite of a relief hole—the hole was too small. Picture 3.51 shows other types of relief holes on stays. The upper arrow indicates a typical location for cracks.

Pictures 3.53 and 3.55 show examples of cracks on forestay members. These cracks are most likely to occur at a discontinuity or transition along the length of the stay members.

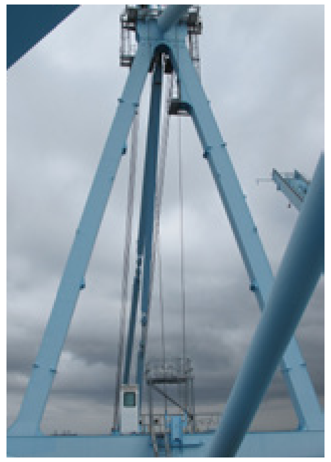
Picture 3.54 shows a crack resulting from a condition similar to that seen on some equalizer beams: the connection sees lateral loads due to wind and other forces; the distance between the top of the girder and the pin connection is wide and short, making the connection stiff in the lateral direction.

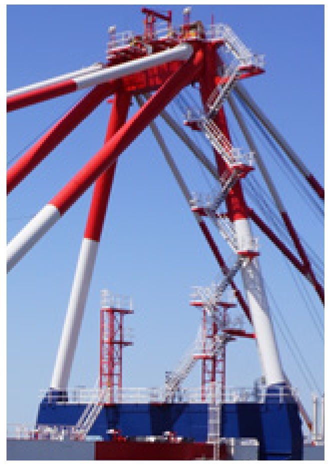
As a result, the connection experiences a significant lateral load that, combined with the main axial load, led to premature fatigue cracking at the base of the plate and failure of some connections, as shown in Picture 2.8.

The connection plates of the forestays at the apex of the crane are also frequent crack locations and should be regularly examined.

Attachments on the forestays, as on all other members, create stress concentrations that should be examined. Any weld to an FCM member is a potential source of a dangerous crack, including welds of small attachments such as lubricating lines or other hardware.

3.13 APEX LEGS, WATERSIDE - NFCM





Pictures 3.56, 3.57 & 3.58: Crane with a single apex tower, viewed from the landside.

The apex legs carry the vertical component of the load from the forestays and upper diagonals and are typically in compression.

Note that the design shown in Picture 3.58 increases the number of stress cycles from the moving load in the waterside TGSB compared to the designs shown in Pictures 3.56 and 3.57 because all stress ranges in the forestays are transferred through the tower, or leg, into the TGSB.

The apex legs are not fracture critical.

3.14 APEX BEAM - FCM

Picture 3.59: Apex beam seen from waterside with forestays on the outside and boom hoist in centre.

Picture 3.60: The same beam from the side with arrows showing typical forces at the apex.

Picture 3.61: A similar view as in Picture 3.59, except from the landside.

Twin girder cranes have an apex beam, as shown in the photographs above. Monogirder cranes, as shown in Pictures 3.56 and 3.58, typically do not have this member. In both cases the fundamental flow of forces is the same.

Picture 3.60 has been marked to show the tension load from the forestays, the tension load in the upper diagonal that carries the horizontal component of this load, and the upward compression in the apex legs that carries the vertical component of the load from the forestays and upper diagonals.

The connections of the forestays, backstays, and upper diagonals at the apex are fracture critical. Typically these connections are arranged so that they are in line with the apex legs, and consequently there is little or no bending in the beam itself from these fluctuating loads - and crack growth in the beam is unlikely. Some exceptions to this arrangement exist.

The connection of the boom hoisting gear to the apex beam is fracture critical -this equipment can be seen on top of the girder in Picture 3.59. Poor details at this connection have led to collapse of some container cranes.

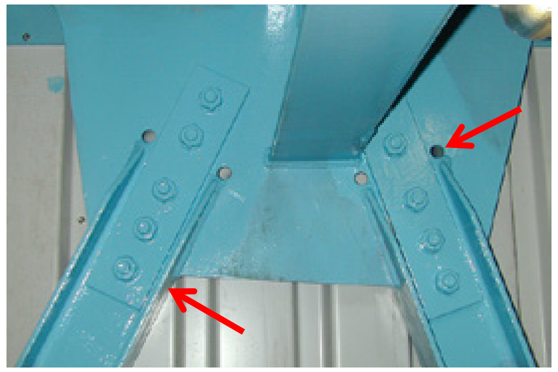
3.15 MACHINERY-ON-TROLLEY HANGERS - FCM

Pictures 2.2 and 2.3 show examples of trolley diagonal fatigue failure.

Picture 3.62: Main carrying members on trolley frame.

Picture 3.63: Trolley members inside machinery house.

Picture 3.64: Pinned joint at center of trolley frame to allow flexibility and reduce secondary bending due to warping of frame during operation.



Picture 3.65: Trolley members with likely crack locations indicated.

Picture 3.62 shows the main tension members that transfer the load from the underhung trolley to the trolley wheels and trolley girder.

Pictures 3.63 and 3.65 show tension members inside the trolley house that connect to the hanger members above and transfer the load from the floor of the trolley, which carries the hoisting equipment. All these members are fracture critical.

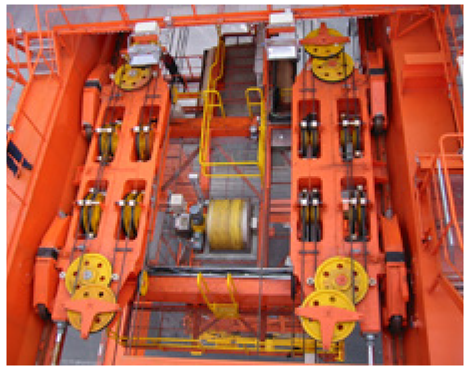
The member connections shown in Picture 3.65 were reinforced with bolted plates and improved with stress relief holes after a number of these connections failed due to trolley warping and poor detailing.

An underhung machinery on trolley experiences tension and bending loads with every lifted load. Some trolley designs experience high stresses because they are designed as rigid boxes that do not allow for height differences between the trolley wheels and the resulting warping of the “box” frame.

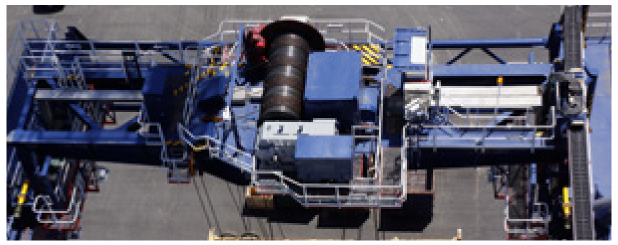
As a result, differences in the height of the trolley rails result in large stresses in the trolley diagonal members. Picture 3.64 shows a special hanger member built into the center of such a trolley to allow the structure to flex.

Because of limited access, particularly at the connections, machinery trolley members are typically difficult to inspect. Historically many trolley members have failed and owners must pay careful attention to the problems of this design.

3.16 OTHER TROLLEY TYPES - FCM



Picture 3.66: STS continuous rope support trolley.



Picture 3.67: The second trolley on a modern STS crane.

Picture 3.68: An underhung rotating RMG trolley.

Picture 3.69: RTG trolley that is also suitable for ASCs.

Picture 3.66 shows a trolley for a rope-towed type crane with continuous rope support. While the continuous rope support is a special feature, the critical members on this trolley are typical for any type of rope-towed trolley crane with the hoist fixed in the machinery house.

The beams, formed of channels on each side of the vertical sheaves, carry the rope load into the perpendicular end beams that bring the loads to the trolley wheels. Each of these members is fracture critical.

Picture 3.67 shows the shore-side trolley on a twin trolley STS crane. In this case, the hoisted load is supported directly on the two beams that carry the load out to the trolley wheels. Because of the distance between the legs and portal beams, the trolley is wide and the bending stresses are significant.

In this regard, this trolley is similar to the trolley on a cantilever RMG crane, where the load is lifted over the sill beam. The two main beams in Picture 3.67 are fracture critical.

Picture 3.68 shows an underhung rotating trolley of an RMG crane designed for rail service. In this case, the main beam, the hanging trolley structure, and the rotating underhung connection are fracture critical.

Picture 3.69 shows a typical RTG crane trolley. The critical members are again the cross beams that support the hoisting machinery and carry the load out to the trolley wheels. The design of automated stacking crane (ASC) trolleys is similar to this design.

3.17 ADDITIONAL AREAS TO CONSIDER - FCM

Picture 3.70: Machinery trolley hoist drum on left and rope direction change and dead end on right.

Picture 3.71: Main hoist sheaves at the backreach. These structures are fracture critical.

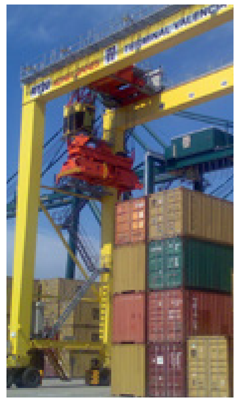
Picture 3.72: Washing and festoon platform hanger at end of girder. The arrow points to a crack indication at the end of the connection plate. The platform is lightly loaded, but bounces up and down during operation.

Other important areas to look at on cranes include the structures supporting the main hoist drums, any hoist rope anchor points, and sheave support structures where main hoist ropes change direction.

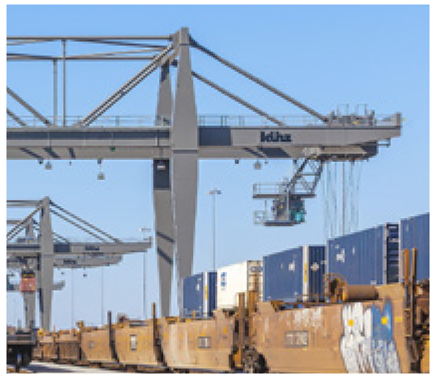
If a crane has heavy but flexible platforms supported on hangers, for example, at the rear washing and festoon service platforms on STS cranes, these hangers may be loaded cyclically by the bouncing and swaying of the crane during normal operations.

Picture 3.72 shows a crack on one such member. Failure of the member can result in dropping the platform.

3.18 ADDITIONAL COMMENTS ABOUT RMG AND RTG CRANES



Picture 3.73: Bracing between the legs of an RTG. This is also typical on ASC cranes.



Picture 3.74: A rail handling RMG crane with truss type main girders and cantilever.

Picture 3.73 shows the trolley, legs, main girder, and leg bracing on an RTG. A similar structural design is used on ASC cranes and some manufacturers use identical structures for ASCs and RTGs. The bracing members shown are not fracture critical. The upper main cross beams sitting on the legs and the trolley cross beams carrying the load are the main fracture critical members on these cranes.

Picture 3.74 shows a cantilever RMG crane. Between the legs, the bottom of the main girder is in tension. On the cantilever section beyond the leg, the inclined diagonal is carrying the load in tension.

CONCLUSION

Identify the tension members and the FCMs and look at the connections. Follow the load path from the moving load. Consider other sources of cyclic loading such as flexing of the structure, or gantry driving loads.

Look for attachments at critical locations, poor details, and other factors that create stress concentrations.

Make regular visual inspections, but engage a professional to make in-depth examinations of the critical points on your cranes on a periodic basis. The crane maker or an expert should identify the critical locations and the inspection intervals.

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