4 STRUCTURAL STEEL

4.1 GENERAL

Most metal bridge superstructures and substructures in New Zealand are of predominantly low carbon steel ("mild steel") construction although some, often notable, structures still stand from an earlier era when wrought iron, cast steel and cast iron materials played a significant part in bridging works. More recent examples of steel bridging may incorporate high-tensile steel or stainless steel components and fastenings. For the purposes of evaluating the condition of bridges, references to steel may be considered to apply equally well to iron unless explicitly stated otherwise.

Steel bridge components usually take the form of sections hot rolled to standard sizes or plates formed to standard dimensions. The standards used for bridge components constructed in pre-metric days are now likely to be obsolete. Steel bars, tubes, cables and castings may also have a structural function in some bridges.

Steel bridge components will generally be fastened with rivets, mild steel bolts, high-tensile steel bolts, or some patented fastening device, or may be welded. Fastenings may be designed to act in shear as individual members or may be intended to provide a clamping force across an interface to permit the generation of frictional forces between adjacent components.

Although some use has been made of specially alloyed steels, the durability of the structural iron and steels in general use in New Zealand bridging generally depends on the locality in which the structure is built, and on the quality and integrity of the protective coating. Rates of corrosion of unprotected metal vary considerably from region to region with some coastal and geothermal areas presenting very severe conditions for structural steel. Similarly, the life and performance of protective coatings vary significantly between regions. Coatings on different parts of a structure will also tend to break down at different rates.

Structural repair and maintenance of steelwork includes the replacement and maintenance of protective coatings, repair of corroded members, replacement of damaged members and defective fastenings, and remedial work associated with fatigue cracking. These problems will have been identified during the inspection and evaluation process.

More detailed information on the painting of bridges is given in Appendix 13.2.

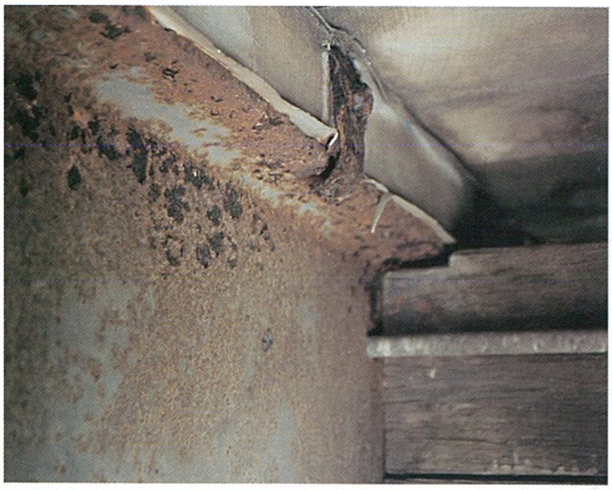

Figure 4.1: RSJ span before maintenance.

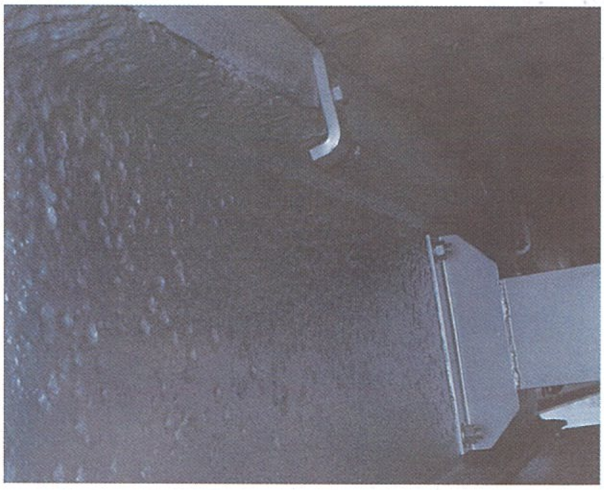

Figure 4.2: RSJ span after maintenance.

4.2 MATERIAL PROPERTIES

In the forms most frequently encountered in bridge structures, steel is strong in both tension and compression and possesses excellent ductility. It is usually only in its cast forms that steel has unremarkable tensile properties and is brittle in nature, although some high-tensile steels have relatively poor ductility. Quality control during production ensures that steels have consistent, predictable and dependable properties, particularly when stressed within the elastic range. Stresses produced by service loads should always lie within this range, so bridge members recover to their original state when loads are removed.

Under significant dynamic loads, or when subject to fluctuating tensile stresses above a critical level, steel members may fracture as a result of fatigue after a certain number of stress cycles. Fatigue behaviour is not affected by the type of steel or, in other words, high-strength steels do not have better fatigue properties than ordinary mild steels. However, fatigue behaviour is very much influenced by the presence of stress concentrations such as holes, welds, abrupt changes of shape, cracks or other defects.

Figure 4.3: Coating failure caused by inadequate primer.

Figure 4.4: Failure of wax barrier coat.

4.3 DEFECTS

4.3.1 General

Defects in a steel bridge will generally appear as a result of the environment in which the bridge exists or as a result of a planned (or unplanned) loading history. Defects may also have been incorporated into a structure at the time of its construction through poor detailing, workmanship or manufacture.

Figure 4.5: Incompatible coatings (alkyd paint over zinc-rich).

4.3.2 Protective Coating Failure

It is rare for a protective coating to outlast the life of the structure.

Breakdown of paint or loss of galvanizing is inevitable, and should be anticipated. The rate of breakdown depends on a number of inter-related factors, with 'time of wetness' being the most important. This usually results from condensation and may be increased by absorption of moisture by wind-borne salts on areas not subject to rain washing. Accumulation of debris, bird droppings, flaking paint etc. will all retain moisture and promote corrosion.

In addition to eventual failure of a coating system by weathering, premature failure may result from:

- Loss of coating adhesion due to faulty specification or application;
- Incompatibility of successive coats;
- Subsurface rusting due to inadequate surface preparation and/or priming paint;
- Localised failure due to mechanical damage;
- Inadequate film-build on sharp edges, welds and paint 'shadow areas'.

In some cases, specialist advice may be required to establish the cause and recommend suitable remedial action.

Figure 4.6: Loss of adhesion (inadequate surface preparation).

Figure 4.7: Damp patch caused by accumulated rust and debris.

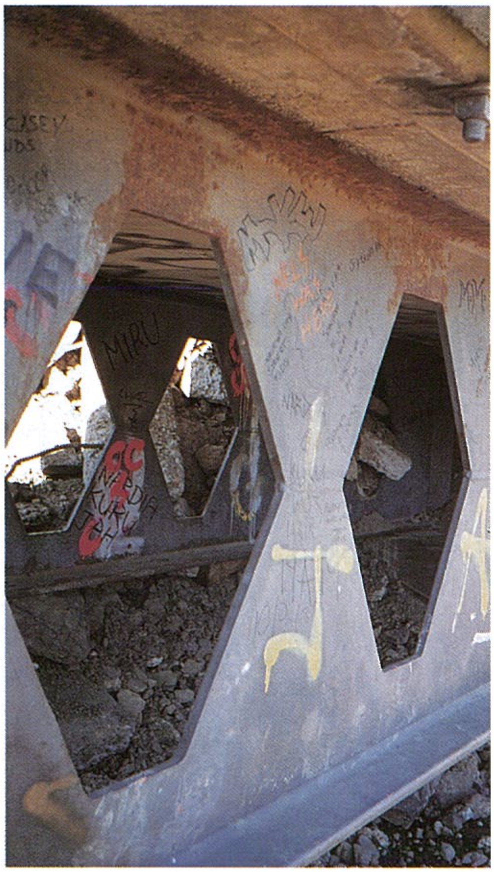

Figure 4.8: Effect of rainwashing: removal of marine salts by rainwashing has kept bottom of outer beam corrosion-free for 14 years (red lead/MIO alkyd system).

4.3.3 Loss of Section

Where the protective coating has not been maintained or an area of damaged coating not been repaired, corrosion resulting in a loss of section usually follows. The corrosion rate largely depends on the proximity of the bridge to the coast.

Corrosion can also be accelerated by the following situations:

- Presence of cracks and crevices;
- Different metals in contact;
- Stray electrical currents;
- Ponding of moisture;
- Concentration of salts through evaporation;
- Chemical attack.

Loss of section may also result from wear in pins or from mechanical abrasion where members rub together

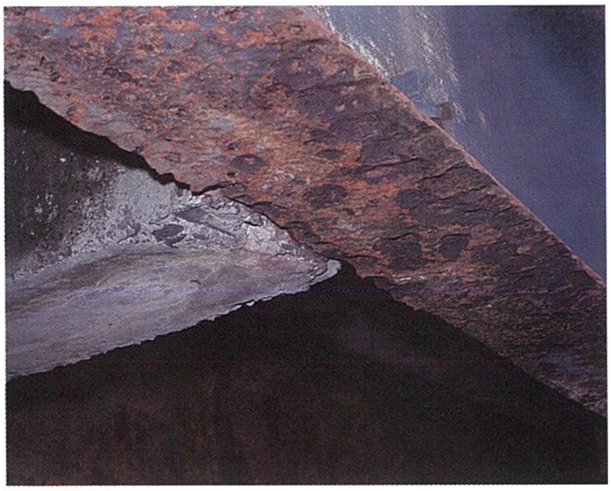

Figure 4.9: Loss of section: severe pitting due to condensation and concentration of salts on bottom flange (and lack of maintenance).

4.3.4 Loose or Defective Fastenings

Whether operating in shear or in a friction grip joint, fastenings must be properly installed to function correctly. Sometimes, because of excessive vibration, over-straining, corrosion or improper installation, fastenings can become loose and should be replaced.

Specific problems typically associated with various types of fastenings are:

- Rivets can become loose and can also suffer from loss of head section if the protective coating is not maintained;
- Mild steel bolts tend to corrode rapidly if the protective coating is not intact. This type of bolt may also loosen with vibration unless suitable washers or lock nuts are provided;
- High-strength bolts will also corrode unless the protective coating is maintained. Galvanized bolts are usually better than painted 'black' steel. Improperly torqued bolts will loosen and bolts which have been installed through heavily tapered flanges without suitably tapered washers may flex and become overstressed;
- 'Huck' fasteners might not be installed to the manufacturer's specifications. The collar must be correctly swaged onto the pin which must be of the correct length for the particular joint. Improperly installed fasteners are unlikely to provide the correct clamping force across a joint. Even when using galvanised fasteners, the collar needs a full protective coating to prevent corrosion;
- Nuts might be of a material incompatible with the bolts or the material being joined. This may lead to electrolytic action if not separated by a non-conductive washer;
- Load indicating washers might be incorrectly installed. The gap provided by the protrusions can be outside the manufacturer's tolerances;
- Spring washers can corrode and/or fracture.

Figure 4.10: Debris around bearings retains moisture.

4.3.5 Cracks

Cracking of any bridge component is potentially serious and needs to be thoroughly investigated. Cracks in steel bridge members can be caused by metal fatigue, embrittlement, impact damage or manufacturing defects such as rolling flaws, and can extend with time. Structural cracks are most likely to have started at obvious stress concentrations such as a bolt or rivet hole, extremities of welds, abrupt changes of section, or at nicks and notches.

Fatigue cracks might not become obvious until a member has been subject to a large number of stress reversals or fluctuations. Some such cracks grow to a certain length and stabilise, but generally they will continue to grow until a critical length is reached. At this point, sudden fracture will occur. Inferior welds, holes and other geometric anomalies and old corrosion pits are common starting points.

Steels with poor ductility characteristics can crack suddenly under impact loads, particularly at low temperatures. Such brittle fracture will initiate at a point of high local stress. Modern structural steels are usually 'notch ductile' steels and do not have this problem.

Rolling flaws or areas of delamination may show up as cracks in structural sections, sometimes many years after construction.

4.3.6 Impact Damage

Accidental damage to bridge members through vehicle impact is, of course, a serious matter and one which needs to be investigated promptly. Through-truss bridges are particularly prone to this type of damage and underpasses also get struck by high loads. Obvious damage will usually be in the form of bent and distorted members and overstrained fastenings, but cracks and nicks from which future fatigue cracks can propagate may also result.

4.3.7 Deformation and Distortion

A structural member's resistance to compressive forces is considerably reduced if components are buckled or distorted out of plane. Tensile members can act unpredictably. Deformation and distortion can occur as a result of:

- Accidental damage;
- Axial over-strain;
- Excessive shear in thin webs;
- Seized bearings;
- Inadequate provisions for expansion.

Deformations cause members designed for tension being forced to take compressive loads. Substructure settlement may also lead to distortion in members.

4.3.8 Manufacturing Defects

Despite the rigorous specifications and the tight manufacturing tolerances to which structural components are rolled and formed, manufacturing and fabrication defects can and do find their way into completed structures.

Rolling flaws may show up as delaminations, cracks, blisters, pits or inclusions as well as out-of-tolerance straightness or lack of squareness. Such defects may be of little consequence, or they can help to initiate a future serviceability problem.

Inferior welds and rough gas-cut edges can lead to major structural problems. A poorly formed or undercut weld, the presence of slag inclusions or the effects of frequent starting and stopping could lead to an eventual fatigue problem. Unfortunately, few welding defects are observable, particularly once a structure is in service.

4.3.9 Faults in Detailing

Regrettably, defects can be built into a bridge structure through poor design, detailing and specification.

Generally, such oversights are the result of people being unaware of the significance of certain features on the long-term serviceability of a structure. In this category are found such details as:

- The abrupt curtailment of steel section flanges in tension members;
- Excessive eccentricities (both in plane and out of plane) in joint intersections;
- Inadequate provision for rotation;
- Poor drainage provisions;
- Curtailment of welds in inappropriate locations.

4.4 INSPECTION

Steel bridges are inspected with the purpose of identifying any defects that may be present in the structure and to establish causes for these defects. Defects that are likely to affect the strength, safety or serviceability of a bridge are programmed for attention as part of the remedial and maintenance work cycle.

An inspector should have a good understanding of a bridge before it is inspected. This is particularly important for complex bridges. Where appropriate and available, the following data sources should be referred to before starting an inspection:

- Plans and drawings (including those showing modifications to the original structure);
- Photographs (both recent and historic);
- The most recent inspection reports;
- Recent maintenance history;
- Strength and rating calculations (for both static and cyclic loading conditions if available).

A visual inspection will systematically cover the whole surface of the steel structure at close quarters paying particular attention to areas which:

- Are highly stressed;
- Undergo significant stress reversal;
- Are poorly detailed;

- Have been observed to be defective during previous inspections.

The following matters are critical to the success of a steel bridge inspection:

- Detailed notes must be taken of the condition of the protective coating on all parts of the structure using a standard method of assessment (e.g. ASTM D610 for rust ratings). Dimensions and locations of significant areas of loss of section should be noted;
- Signs of rust staining should be looked for around the heads of fasteners. This may indicate that they are loose. Confirmation can be obtained by lightly tapping the fastener with a hammer;
- Fasteners which do not conform with proper standards of installation should be noted;
- Cracks will usually show in the first instance as a trace of rust emanating from a stress raiser. The highest loaded bolt or rivet in a joint should be carefully examined in areas which are expected to be susceptible to fatigue. Particular attention should be paid to the ends and edges of welds. Secondary loading effects should be taken into account when looking for possible cracks;
- The presence of a suspected crack should be confirmed by non-destructive testing, by an operator certified by New Zealand Certification Board for Inspection Personnel (CBIP) using suitable equipment. Dye penetrant and magnetic particle techniques are likely to be used in the first instance. Radiographic and ultrasonic methods may also be used for specific cases;
- Deformations and distortions will often show up as cracking or flaking paint. Any deviation can be picked up by sighting along the line of a member. Measurements of any significant deviations from the true line should be recorded;
- Probable causes of defects should be determined if possible at the time of inspection. If a cause is not immediately apparent, specialist advice may be needed.

The location and description of all defects must be methodically recorded to allow proper evaluation of their effects and subsequent monitoring or repair.

Figure 4.11 shows possible faults in a steel beam.

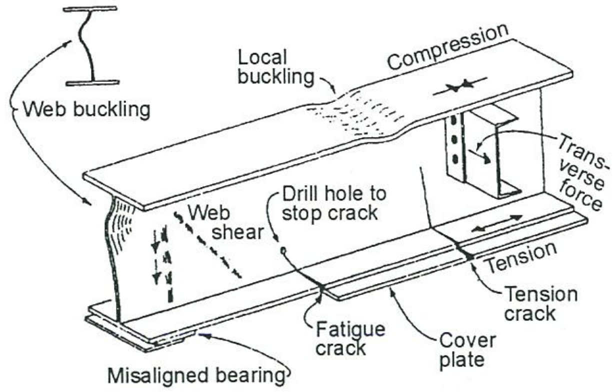

Figure 4.11: Possible faults in a steel beam.

4.5 EVALUATION

In one way or another, all observed defects will have an effect on the strength or serviceability of the bridge. Defects which reduce the capacity or durability of the bridge or which present an immediate serviceability problem do require remedial action, but others may not. The purpose of evaluation is to determine the relative significance of each defect so that the load-carrying capacity of the bridge can be reassessed and so that any remedial work required can be given proper priority. Evaluation will also assist in determining future strategies for maintenance or replacement.

The evaluation of the effect of some defects can be a complex process requiring a thorough understanding of the behaviour of the structure concerned. The interaction of primary and secondary load-carrying members, the effect of imperfectly pinned joints and the possible presence of alternative load paths need to be appreciated. A basic understanding of metal fatigue and crack mechanics is necessary to evaluate problems of this nature. The risk of failure of certain members and to the consequences of such failures may need to be considered.

The allowable load factors or material stresses used to evaluate the effect of a condition are provided for in the Transit New Zealand "Bridge Manual" (SP/M/014). The frequency and type of traffic, the age and remaining life of the bridge and the size and importance of the bridge will all need to be considered in arriving at appropriate parameters. Primary load-carrying members such as main beams might need to be treated differently from secondary members such as bracing components.

Analysis of all members is required to assess the safe allowance loading for the bridge. Procedures should follow those set out in the Transit New Zealand "Bridge Manual" (SP/M/014).

If there is any doubt about the validity of the theoretical analysis, rating results for particular members in complex structures should be verified by strain gauging and test loading exercises.

4.6 REPAIR OF PROTECTIVE COATINGS

The level of maintenance required will generally be determined by the condition of the coating but the maintenance strategy will be influenced by the ease of access. Often, removal of accumulated debris and washing of contaminants from the coating surface are all that is necessary. A regular cleaning programme with minor spot painting will greatly increase the useful life of the protective coating.

To maintain in good condition a shop-applied, high-quality system it is usually more economic to carry out programmed maintenance painting than allow it to completely degrade and then attempt to replace it *in situ*. A field-applied coating is unlikely to give the same performance. Early and regular maintenance to touch up minor defects or upgrade areas with inadequate protection will allow any system's full potential to be achieved and is strongly recommended.

For small items (e.g. handrails and brackets) that are severely degraded, it may be more economic to remove them and hot-dip galvanise rather than repaint, as shown in Figure 4.12.

Figure 4.12: Pitted steel posts refurbished by galvanizing.

4.6.1 Surface Preparation

After the removal of contaminants from a coating's surface by rain or maintenance washing, the next most important factor affecting the life of a protective coating is the surface condition and cleanliness at the time of its application. Where rust exists it is usually cost-effective to remove it by abrasive blast cleaning, after first washing to prevent contaminants being driven into the steel surface. The use of so called "rust-converters" is not recommended as their performance in independent tests against conventional systems has usually been disappointing.

The degree of surface cleanliness required is usually based on a Standard such as SIS 05 5900 or AS 1627.9 which contains descriptions and photographs of different initial surface conditions of rust (e.g. Class D for pitted steel) and corresponding descriptions and photographs for various grades of preparation using hand tools (St grades) and abrasive blast cleaning (Sa grades). Grade Sa 2½, for example, describes a "near-white metal" surface finish and is equivalent to an AS1627.4 Class 2 ½ or SSPC-SP 10 finish.

Appropriate safety precautions for cleaning and recoating steelwork coated with lead-based paint are given in Transit New Zealand Specification TNZ C/26:2000.

In some situations, rust can only be removed by mechanical methods. In this case care should be exercised to ensure the surface is not burnished which will reduce adhesion. Relevant standards are AS 1627.2 (power tool) and AS 1627.7 (hand tool).

High-pressure water-blasting is a useful method of removing aged or non-adherent coatings and contaminants, but some coatings (e.g. epoxies and urethanes) may require a light abrasion to provide a mechanical key for subsequent coats to adhere to. This is not necessary when upgrading solvent-borne coatings such as chlorinated rubbers and vinyls.

Where failure has resulted from the coating cracking at sharp edges or rough welds, these should be rounded or smoothed by grinding before re-painting. Similarly, thick edges of remaining paint layers should be feathered by hand sanding.

4.6.2 Coating System Selection

Many variables must be considered when selecting a maintenance coating system. Important factors are:

- Compatibility with existing coating;
- Standard of surface preparation achievable;

- Climatic conditions under which re-coating will be carried out;
- Whether time constraints exist.

In addition, other relevant factors are:

- Ease of future maintenance;
- Number of coats required;
- Appearance;
- Proven performance in similar environment;
- Whether application is to be by unskilled labour or by a contractor with specialist equipment.

AS/NZS 2312 "Guide to the protection of steel work by the application of corrosion resistant coatings" discusses these factors and contains a step-by-step check list to help in the planning of a coating maintenance project. It is an essential reference for coating selection.

Pre-1970 systems based on red lead primer applied to flame-cleaned steel have been superseded by higher performance, chemically cured paints applied to abrasive blast-cleaned steel. Zinc phosphate-based primers are suitable for hand-prepared steelwork but zinc-rich primers over blast-cleaned steel provide the best foundation to a long-life coating system.

Chlorinated rubber-based systems were often specified because of their superior resistance to moisture and chlorides. Being solvent-borne, they are also easily re-coated, over-spray problems are minimised, they can be applied at low temperatures, and they are "single pack" products.

Moisture-cured urethane (MCU) systems are now available. These are single-pack materials that are fast drying and are tolerant of a very wide range of climatic conditions. Because of their flexibility and compatibility with a wide range of other coatings they are often used to 'encapsulate' old lead-based coatings, which can cause environmental and health hazards if removed without proper containment.

Finishing or top coats are often pigmented with minute flakes of aluminium or micaceous iron oxide (MIO) to reduce breakdown of the coating (chalking) by ultraviolet rays and to give the structure a metallic appearance. MIO will also reduce the coating's permeability and provide a key for future maintenance.

The performance of coatings which rely solely on barrier action to protect the steel (e.g. epoxy mastics) can be improved significantly by the use of a primer which resists undercutting when the barrier is damaged or defective. Use of barrier coatings alone is often not cost effective, especially when applied over residual rust.

The thickness and number of coats required will be determined by the severity of the environment, and the planned time to next maintenance. It is often beneficial to give the members most at risk (e.g. the bottom flanges of girders) an extra coat.

Codes of Practice such as AS/NZS 2312 give recommended dry film thicknesses but, for major structures, advice from a paint manufacturer or independent coatings consultant should be sought. As well as paints, the use of thermal metal spray or galvanizing should be considered within the context of the structure's total life cycle cost.

The NZ Paint Approvals Scheme (PASS) provides members with lists of approved paint brands that have been found to comply with composition or durability requirements of its specifications and that are manufactured within an approved quality assurance system. Further information may be obtained from TELARC, Private Bag, Remuera, Auckland.

4.6.3 Application and Supervision

The weak link in a painted system is usually at sharp edges where it is difficult to obtain the specified coating thickness, especially when applying by spray. It is therefore recommended that before each main coat is applied, a "stripe coat" be brushed onto the edges of all flanges, holes, welds and rivets. Similarly, severely pitted surfaces or pin-holed primer coats should receive a second coat of primer.

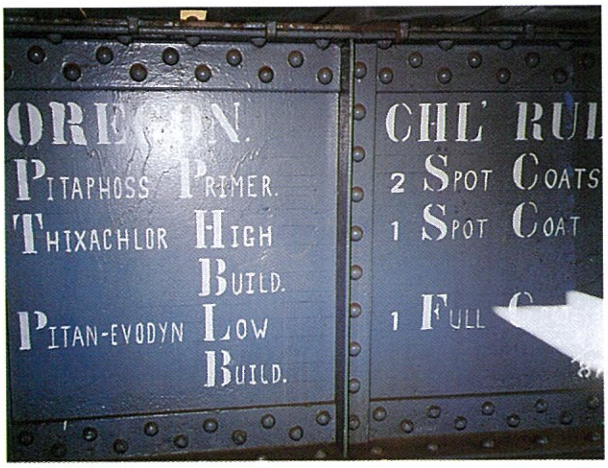

Figure 4.13: Painting record

To ensure that recommended procedures are followed, employment of an experienced third-party coatings inspector (e.g. CBIP-certified) is often a good investment. High-performance systems depend on good surface preparation and application under suitable conditions. As a minimum, daily records should be kept of application times, paint batch numbers, brands used, environmental conditions during application and dry film thickness measurements. Suitable quality control forms are published as AS 3894.10 & 12.

It is recommended that, on completion, details of the surface preparation and the paint type and thickness be stencilled onto a readily visible member for the benefit of future maintenance personnel.

4.7 REPAIR OF DEFECTIVE MEMBERS

The need to repair a defective bridge component will have been established during the evaluation process (Section 4.5).

Because of their relative importance, differing approaches are usually taken with the repair of primary load-carrying members and secondary members.

In many instances, there is a choice of either replacing a defective component in its entirety, or providing some sort of splice or strengthening plate, taking into account any introduced eccentricities. There is usually also a decision to be made as to whether the replacement or supplementary member will carry dead load as well as live loads. The final choice of method will take into account the ease of component removal and replacement, cost factors and the degree of deterioration of the component.

Provided other members can carry all the dead load as well as their share of the live load without detriment to the capacity of the structure, it will generally prove simplest to have the replacement member carry no dead load. This will require minimal temporary support and there will be no need to calculate and provide the proper degree of prestress during installation in order to allow for dead load. If, however, it is essential that the new member carries its full share of dead load, installation becomes considerably more difficult. Methods involving full temporary support for a section of the bridge, relieving frames, preheating the new component, or one of several methods of tie shortening could be required.

It may be possible to straighten bridge components that have been bent and deformed as a result of vehicle impact or some similar event to an acceptable state after heating the affected area. Nicks and gouges may be ground out to remove local stress-raisers, and cracks prepared and welded. Clearly, this sort of treatment is only possible if the resulting static and dynamic ratings of the repaired member are acceptable. Alternative methods for this type of damage include member replacement or lapping with additional components.

Loss of cross-sectional area in steel members through corrosion may need to be repaired even if the strength of the structure is not affected. For instance, corroded girder flanges may be so pitted that water is retained for long periods and corrosion remains active. An epoxy filler could be applied to a mechanically cleaned surface to improve drainage and extend the useful life of the member.

Buckling in members can often be relieved by investigating and removing the cause of the problem rather than by treating the member concerned. In some cases, however, a member may need additional stiffening or bracing, or may need to be shortened. This type of work should not be initiated without first considering the effect of a stiffer or shorter member on the remainder of the structure.

4.8 REPAIR OF DEFECTIVE FASTENINGS

Incorrectly installed high-strength friction grip (HSFG) bolts and fasteners can probably best be remedied by replacement with like components installed correctly (after first investigating the reason for the substandard installation).

Loose or corroded rivets may be replaced with friction grip fastenings either singly or in groups. It is probably best to replace the remainder of an entire rivet group once half of the original rivets have been replaced. New fastenings should be painted immediately after installation.

4.9 TREATMENT OF FATIGUE PROBLEMS

Fatigue problems are normally identified in the crack growth stage. Unrestricted, the crack is likely to continue to grow slowly until the critical crack length is reached and sudden fracture occurs. Crack growth can be slowed and sometimes stopped altogether by eliminating the small area of high local stress at the crack tip by drilling a small, smooth hole (perhaps 10 mm or so in diameter) at or just ahead of the tip.

Investigating the reasons for the failure is essential. The general approach to overcoming this type of problem is to eliminate the stress concentrations which have given rise to the fatigue crack and continue to assist its growth, and then to look at ways to improve the situation.

It may be possible to reduce the stress in the area of the crack by introducing new load paths or removing redundant members, especially if secondary forces contribute to the stress intensity, or by re-designing a joint or connection. In conjunction with this work, peening the area of metal at the root of the crack with a pneumatic peening hammer will introduce local surface compressive forces which are highly beneficial in slowing or arresting the progression of the crack.

Cracked welds (where the crack does not extend away from the weld into parent metal) can usually be effectively repaired by grinding out and re-welding the section of defective weld, then peening the weld until plastic deformation causes the metal to become continuously smooth. Peened indentations will be between 0.5 mm and 0.8 mm deep.

Where small cracks have initiated from rivet holes, replacing the rivets with high-strength friction-grip bolts will reduce stress concentrations and introduce compressive stresses across the joint. This method can not be used if the crack has progressed too far from the rivet hole.

If none of these methods are appropriate, the component will need to be replaced. Suitable modifications to the original design must be made to ensure that the stress raiser which caused the problem is eliminated.

4.10 PREVENTIVE MAINTENANCE

The preventive maintenance of a steel bridge starts at the design stage when proper attention should be given to the detailing of components and connections to ensure that they have adequate strength and serviceability for the structure's design life and adequate clearance for future maintenance. Provision of access to facilitate future inspections and maintenance should also be considered. Other practices which will assist in minimising maintenance of an in-service bridge include:

- Proper selection of protective coating type, proper surface preparation and application over the entire coated surface;
- Regular washing and cleaning of protective coating surfaces;
- Regular clearing and cleaning of drainage ports. Improving drainage in areas which are not adequately drained;
- Ensuring bearings are operating correctly;
- Maintaining the presence of adequate expansion gaps.

In addition, potential problem areas should be identified and appropriate action taken before structural defects become manifest. Such matters include:

- Details involving abruptly curtailed cover plates on flanges or sharp re-entrant angles should be improved if they are likely to become fatigue risks;
- Poor welds should be ground out and replaced;
- Selected rivets can be replaced with high-strength friction-grip, fasteners to improve the fatigue characteristics of a rivet group (e.g. the leading rivets in a joint or cover plate);
- Eccentricities in joints and connections may be improved to reduced unwanted bending stresses;
- The point of support of bearings may be redefined to improve eccentric movement effects.

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