2. Review of Insulated Rail Joints (IRJs)

2.1. Introduction

This chapter presents a review of insulated rail joints (IRJs). As safety critical sections of the signalling system in rail networks, the significance of IRJs is presented first in Section 2.2. Various IRJ designs employed worldwide are reviewed in Section 2.3. The failure modes of IRJs are described in Section 2.4 and a hypothesis of failure of the IRJs used in the heavy haul network of the Australian railways is reported in Section 2.5. Wheel/rail contact impact at IRJs that is believed to be the key factor of initiating the IRJ failure is explained in Section 2.6.

2.2. Significance of IRJs

IRJs are used to electrically isolate the rails as part of the system to achieve signal control. Failure of IRJs is a significant safety issue. As such the rail infrastructure owners take extreme care in maintaining the IRJs in sound condition.

Structurally IRJs are designed as bolted joints with each component electrically isolated from each other. As for all types of joints which involve a discontinuity in the rail, IRJs are considered to be weak spots in the rail track. The service life of IRJs is typically 100 MGT, which is considerably shorter than other rail components that withstand as high as 1000MGT (Davis, 2005). The annual cost to the Australian rail industry for the maintenance and replacement of IRJs has been conservatively estimated to be \$5.4 million in direct costs and \$1.1 million in indirect costs annually (RailCRC 2003). Investigation of the failure mechanism of IRJs with a view to improving their performance has, therefore, assumed prominence in recent times.

2.3. Designs of IRJ

IRJs comprise of an insulation material (end post) fixed between the ends of two adjacent lengths of rail, and secured by bolted joint bars that connect the two rails. Several designs of IRJs are reported in the literature. The designs vary in terms of the parameters of the supporting systems, joint bars and insulation end posts.

Two types of supporting systems of IRJs exist depending on the positionings of the sleepers with reference to the end post:

i) Suspended IRJ

ii) Supported IRJ

As shown in Fig. 2.1, the suspended IRJ has the sleepers positioned symmetric to the end post. For the suspended IRJ, there is no support underneath the end post.

On the other hand, for the supported IRJ, the end post is placed directly on the sleepers. There are two types of designs:

i) Continuously supported

ii) Discretely supported

Figure 2.1 Suspended IRJ (RAILFOTO, 2005)

Continuous insulated joints (Fig. 2.2) are continuously supported at the rail base using the specially designed joint bar. A special tie plate known as “abrasion plate” is also used to support the joint.

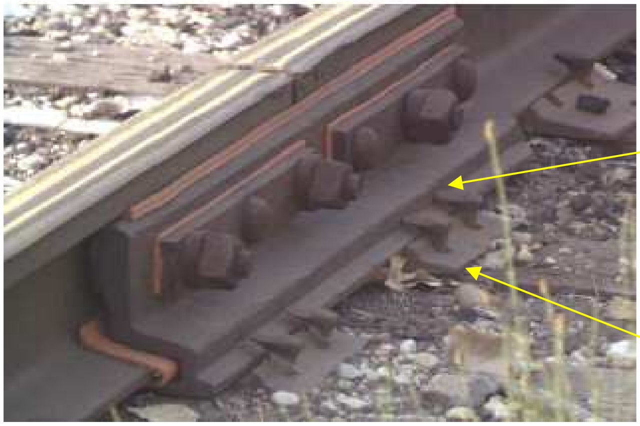


Figure 2.2 Continuously Supported Insulated Joint (AREMA, 2006)

The end post of the discretely supported IRJ is directly placed on a sleeper, as shown in Fig. 2.3.

Fig. 2.4 shows another type of discretely supported IRJ, which employs two sleepers together at the centre.

Figure 2.3 Discretely supported IRJ (LBfoster, 2006)

Figure 2.4. Supported IRJ (Esveld, 2001)

The joint bar designs are characterised by various cross-section designs and the length of joint bar, namely 4-bolt joint bar and 6-bolt joint bar. Various cross-section shapes are shown in Fig. 2.5. For simplicity, instead of showing the symmetric joint bars on both sides of rail, the joint bar on just one side only is presented in this figure.

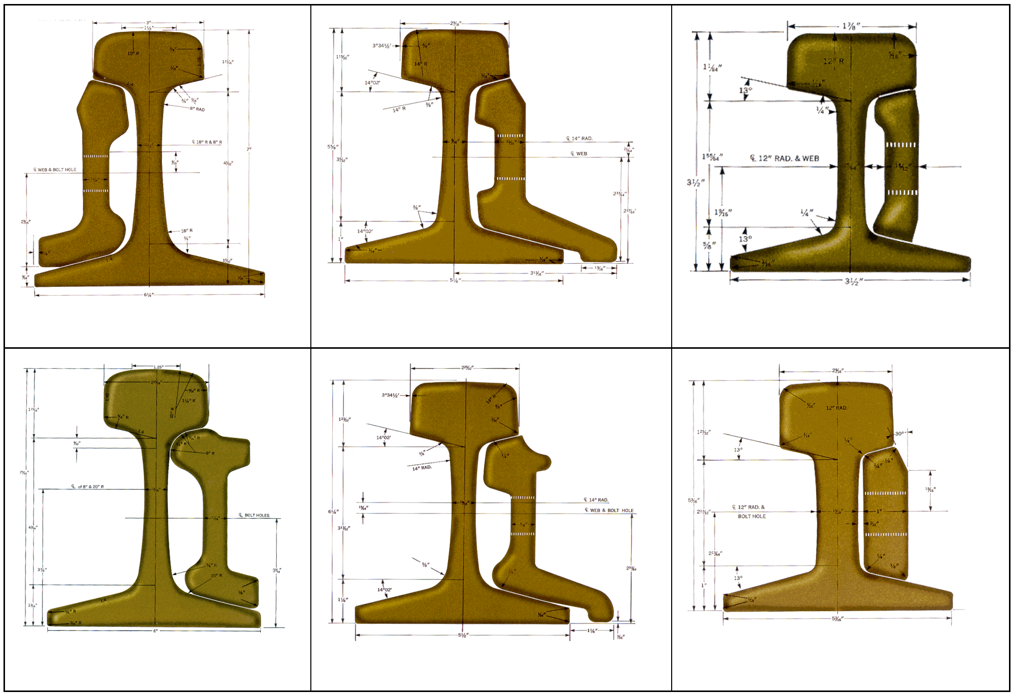


Figure 2.5 Different joint bar designs (AKRailroad, 2006)

The 6-bolt joint bar and 4-bolt joint bar are the two most common designs; a 4-bolt joint bar is shown in Fig 2.1 and a 6-bolt joint bar is shown in Fig. 2.6. The 6-bolt joint bars are obviously longer than the 4-bolt joint bars.

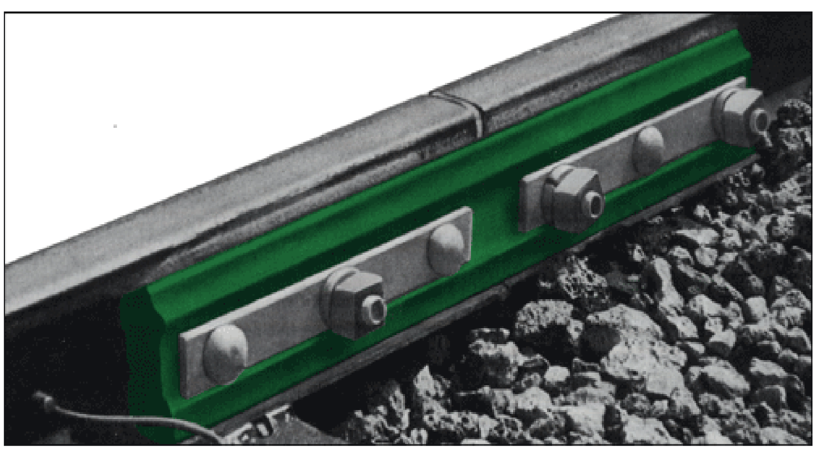
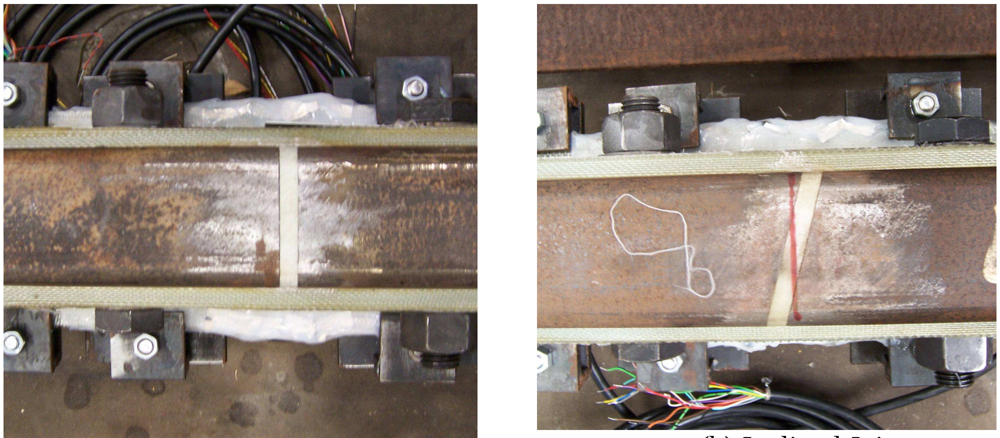


Figure 2.6 IRJ with 6-bolt joint bar (LBfoster, 2006)

Joints are also made either square or inclined to the longitudinal axis of the rails. Fig.2.7 shows examples of these types of joints.



(a) Square Joint (b) Inclined Joint

Figure 2.7 Types of Insulated Rail Joints

The properties of the end post materials play an important role in the response of the IRJs. Polymer, Nylon and Fiber-glass are the commonly used IRJ insulation materials. In addition, the gap size (thickness of end post material) is also varied from 5mm to 20mm and is a key parameter for the IRJ design.

The design of IRJs also differs with the detailing of end post fitting between the rails. Glued IRJ and inserted IRJ (non-glued) end posts are two common forms employed. The glued IRJs use adhesive material such as epoxy to ensure full contact between the steel joint bars and the rail web whilst they remain electrically insulated. The inserted IRJs are a simple insert of the insulated materials into the end post gap with thermal treatment but without any adhesion material.

Some novel designs of IRJs appear in the market with a view to enhancing the structural integrity of the joints. Fig. 2.8 shows an encapsulated IRJ design used in Canada with the Polyamide 12 as the insulation.

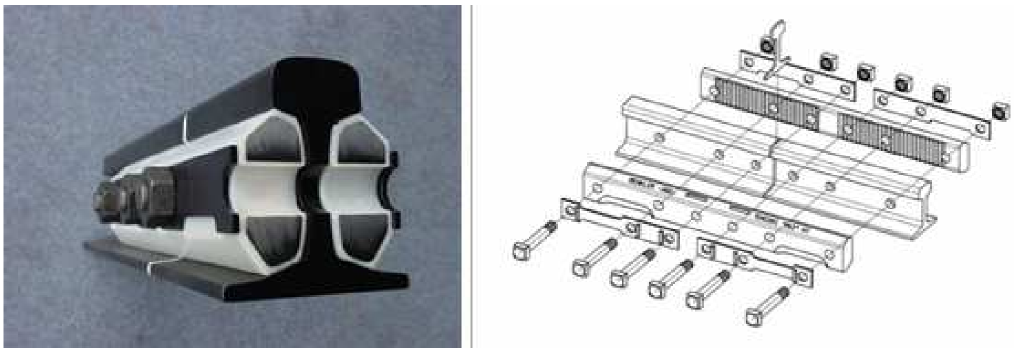


Figure 2.8 Novel design of IRJ in Canada (Nedcan, 2006)

The IRJs, like other rail circuits, are laid on the “beddings” which contains several flexible layers. Two types of tracks exist, namely, ‘conventional’ ballasted track and ‘non-ballasted’ (for example slab-track) track. Most of the Australian railway tracks are traditional ballasted and hence in this thesis only the ballasted track is chosen as the rail bedding. Referring to Fig. 2.9, IRJs are fixed to the sleepers by fasteners. The sleeper pads are inserted between IRJs and sleepers. The ballasted track substructure contains three layers: ballast, sub-ballast and subgrade. The first two layers usually consist of coarse stone chippings. The rail track superstructure and substructure together with the wheel/rail interaction constitute a complete IRJ working environment.

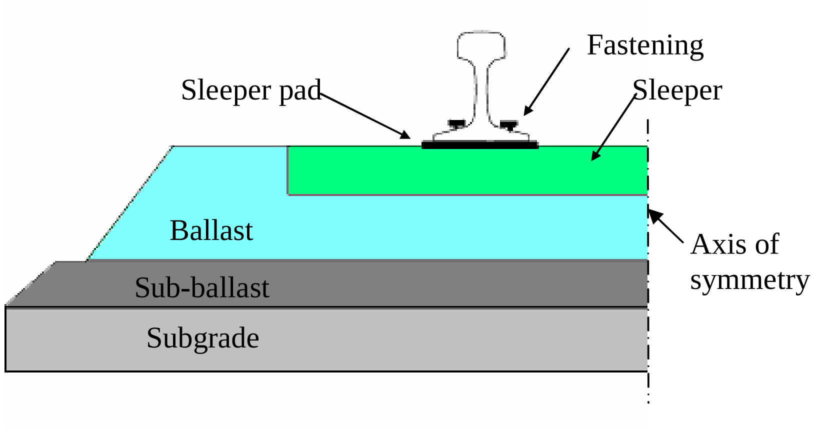


Figure 2.9 Ballasted Track

2.4. Failure of IRJs: An International Perspective

Amongst the various IRJ designs used worldwide, the failure modes of IRJs can be categorised as follows:

i) Bond failure/delamination of end post

ii) Loosening of bolts

iii) Broken joint bars

iv) Battered /crushed end posts

v) Metal flow/material fatigue on rail head

These failure modes, with one aggravating to the other, leading to a vicious circle accelerating the overall failure of IRJs. According to survey conducted by Davis (2005), the bond failure is the most common failure mode found in the heavy haul routes of North America due to high level shear stress under severe wheel loads. Fig. 2.10 presents the bond failure of the end post. The wheel/rail contact impact and the longitudinal force due perhaps to thermal effects also contribute to bolt loosening which further worsen the structural integrity and excites higher wheel/rail contact impact forces. This may consequently lead to other failure modes, namely, broken joint bars and battered/crushed end post shown in Fig. 2.11.

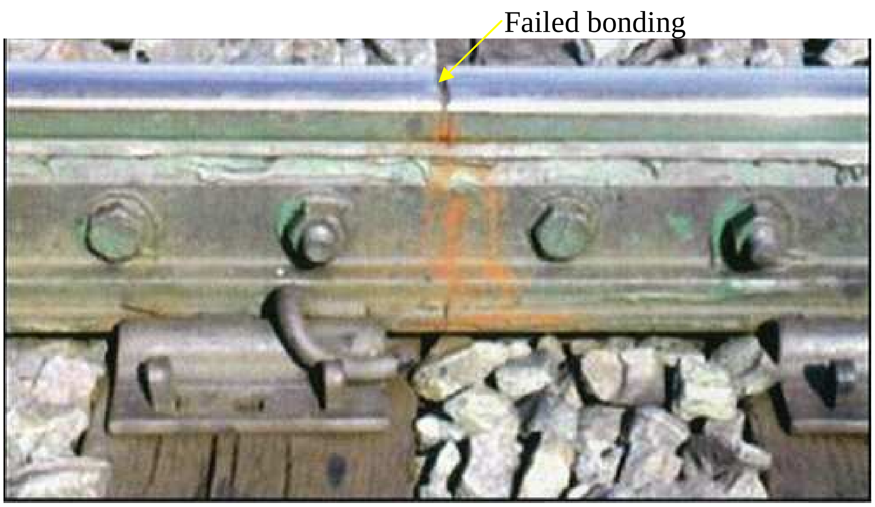


Figure 2.10 IRJ with failed glue bond (Davis, 2005)

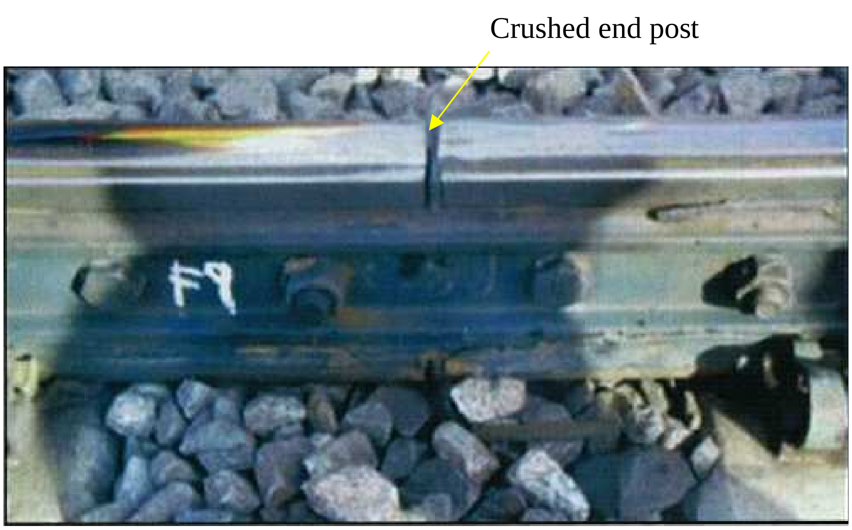


Figure 2.11 IRJ with end post crushed (Davis, 2005)

Railhead metal flow/fatigue is another failure mode that occurs if the broken joint bar or battered end post does not occur. This failure mode starts as defects on the railhead (shown in Fig. 2.12) and progresses to railhead metal failure (shown in Fig. 2.13). One of the key factors that causes this failure mode is the severe wheel/rail contact impact force and the associated rate dependent metal plasticity.

Within Australia, the railhead material failure or metal flow is the most commonly observed mode and hence is focused in this research. Fig 2.13 shows the material failure in the vicinity of the end post. It exhibits railhead metal flow, which leads to contact between the rails separated by the end post, causing critical electrical isolation failure of the IRJ. It is notable that due to the material chipping out, severe geometry discontinuity is generated, which further leads to early structural failure of IRJs.

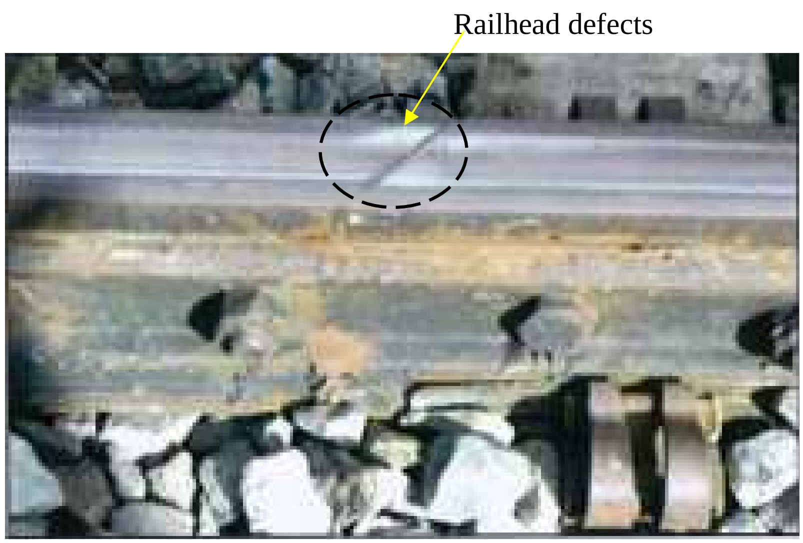


Figure 2.12 Running surface defect of IRJ (Davis, 2005)

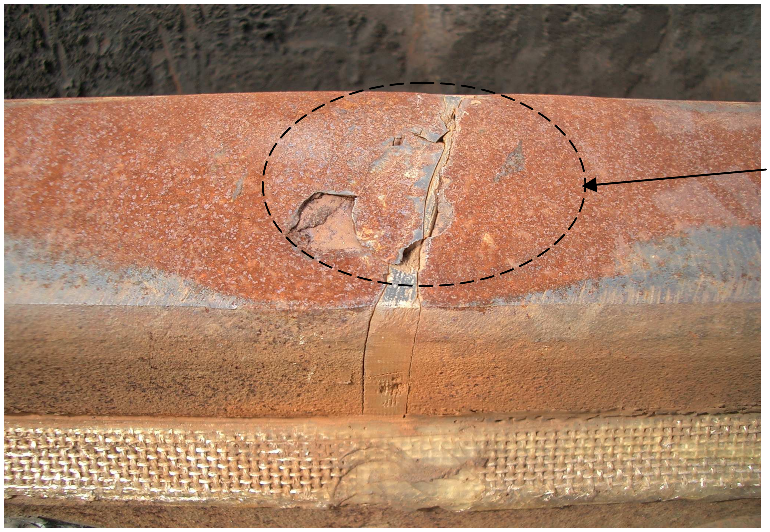


Figure 2.13 Typical IRJ failure in Australian heavy haul networks

2.5. Wheel/rail Contact-Impact at IRJs

To understand the railhead failure mechanism of the IRJs, a quantitative study of the wheel/rail contact impact is important. Many researchers have contributed their efforts to this area recently and have developed various models to investigate the wheel/rail contact impact. Static analysis is always helpful to understand the wheel/rail contact issue; as it is simple, it has been adopted by many researchers to study the IRJ characteristics. The key to investigate the wheel/rail contact-impact is however the dynamic analysis. Rigid multibody dynamics (RMD) and finite element method (FEM) are widely employed to study the wheel/rail contact-impact.

2.5.1. Static wheel/rail contact simulations

Kerr and Cox (1999) established an analytical static loading model of an IRJ. The deflection near the end post was studied using a modified beam model supported on an elastic foundation. The rail sections and joint bars were modelled as linear elastic beams, and the epoxy-fiberglass insulation was simplified as spring layers by employing the Zimmermann hypothesis. The contact load was equally distributed to both rail ends. A static loading test was conducted to validate the analytical model. The test results were found to agree well with the established analytical model. The wheel/rail contact issue was not discussed in their paper.

Yan and Fischer (2000) have carried out a static 3D finite element analysis (FEA) with three different rail models: standard rail, crane rail and a switching component. By comparing the results with the Hertz contact theory (HCT), the authors concluded that the elastic model agreed well with the HCT if the surface curvature of the rail remains unchanged. For the elasto-plastic model, it is found that their numerical results differ from the conventional HCT. The numerical results show that the contact pressure has a lower peak value but flatter distribution than the HCT if material plasticity occurs.

By establishing an elastic 3D FE rail model, Chen and Kuang (2002) carried out a static analysis of an IRJ subjected to vertical wheel loadings. They found that the traditional HCT was not valid for predicting the contact pressure distribution near the joint. The idealised elliptical contact dimensions were also listed to point out the differences with the HCT predictions.

Chen and Chen (2006) presented a 2D static FE model that was used to study the effect of an IRJ on the wheel/rail normal and tangential contact pressure distribution.

Contact elements were used to simulate the wheel/rail interaction behavior. In their model, different traction and braking forces were applied to investigate the contact pressure and maximum shear stress distribution in the railhead. Their conclusion was that the Hertz theory was not valid near the IRJ due mainly to edge effects.

Chen (2003) also investigated the material elastic-plastic effect to the IRJ under static loading using a 2D static wheel/rail contact model and concluded that the elastic model agree well with the HCT as the contact position from the rail edge over HCT half contact length exceeded 1.5. However, the elasto-plastic model indicated a disparate result that the peak pressure had a smaller value (around 70% of HCT) compared to the elastic model or HCT. With the wheel moving towards the rail end, the Von-Mises stress, plastic zone size increases gradually whilst the contact area and the peak contact pressure decrease.

Wiest et al.(2006) compared four different wheel/rail contact models at a rail turnout to examine the Hertz elastic half-space contact assumptions. Hertzian contact method, non-Hertizan contact method, elastic finite element analysis and elasto-plastic finite element analysis were conducted. The wheel and the rail switch were modelled in the finite element analysis and ‘master-slave’ contact surfaces from ABAQUS /Standard were adopted to solve the wheel/rail interaction. The results showed that the elastic finite element method agreed well with the Hertzian and non-Hertzian method in terms of contact area, peak contact pressure and penetration depth. The results of the elasto-platic finite element model differed to the other three models with a much larger contact area and smaller peak contact pressure.

2.5.2. Dynamic wheel/rail contact simulations using rigid multibody dynamics

For the dynamic analysis of IRJs, rigid multibody dynamics were widely employed in the IRJ studies. Jenkins et al. (1974) studied the dipped rail joints using the rigid body dynamic methods. They modelled the dipped rail joint as a dipped continuous beam supported by sets of springs and dashpots at the location of sleepers. Contact between wheel and railhead is assumed to be of HCT. They predicted the dynamic contact force factors (defined as the ratio of dynamic to static force) between the rail and the wheel at the assumed dipped joints, and found that there existed two contact force factors: the first being a high amplitude (5~6) and high frequency peak (500Hz), and the second a low amplitude (3~4) and low frequency peak (30~100Hz). The first peak damps out in a few milliseconds and affects only the local contact area. The second peak damps slowly and affects most track and wagon components.

Newton and Clark (1979) also studied the rail/wheel dynamic interaction in both experimental and theoretical methods. The contact/impact between the wheel and the rail introduced by wheel flats rolling over the railhead was researched and a comparison of an experiment and theoretical results was carried out. The experiment used an indentation on the railhead and strain gauges were used to measure the strain history. The theoretical model considered the sleeper pad as a spring and dashpot layer, sleepers as a mass layer, and ballast as another spring and dashpot layer resting on a rigid foundation. It was shown that the dynamic effects of wheel flats strongly depend on the rail pad stiffness and the speed regime.

Sun and Dhanasekar (2002) developed a whole wagon and rail track multibody dynamics model to investigate the dynamic rail-vehicle interactions. The rail track was modelled as a four layer sub-structure and the non-linear Hertz spring was employed for the contact mechanism. Several idealised wheel/rail irregularities were imposed as the dynamic load excitations. The results were validated by several published models and experiments, and good agreements were achieved.

Wu and Thompson (2003) developed an efficient dynamic rail wheel contact model for rail joint impact noise analysis. Rail and wheel, which were assumed as elastic bodies, were connected to each other using the Hertz non-linear spring allowing a loss of contact. The wheel centre trajectories were employed to model the dipped joint. The rail foundation was modelled as discrete double layer system with spring, mass and damping parameters to model the pad, sleeper and ballast characteristics. Gap size, vertical misalignment and dip of rail joint were studied. The impact force was shown to have 400%~800% of static load at certain conditions for various velocities and depths of joint dip.

Steenbergen (2006) reported a theoretical 'multi-point contact' wheel/rail model by multibody dynamics to investigate the contact spatial discontinuity in his paper. Through a comparison with the common practical 'continuous single point contact' model which employs the Hertz nonlinear spring as the contact parameter, the author concluded that by using the 'continuous single point contact' the possibility of impact would be automatically excluded and that the situation can be improved by introducing the vertical velocity change to the wheel mass when 'double point contact' occurs. However, the rail irregularities such as the IRJs are treated as steps and kinks, which may not be easy to apply to IRJs without permanent deformations (such as new IRJs).

Recently many researchers developed efficient approaches which coupled rigid multibody dynamics with FEM to study the rolling fatigue, railhead crack and metal plastic flow at the wheel/rail contact surface irregularities which need a strain and stress analysis. The rigid multibody dynamics models were developed to investigate the wheel/rail dynamic contact force. The results were then transferred into the finite element model for the detailed strain and stress analysis to investigate the railhead damage.

Bezin et al. (2005) introduced an approach which coupled a multibody system model and a finite element model together to conduct a rail stress analysis. In this research, a whole wagon/rail multibody dynamics model was developed using ADAMS/Rail. The generated dynamic force was then transferred into a global FE model setup using ABAQUS as the loading condition. In this global FE model, the bending stress and strain of rail and sleeper components established with elastic Timoshenko beam and spring elements were obtained via a static analysis. A local 3D solid finite element contact model was established to study the contact pressure and stress distribution which was essential to predict the crack initiation and growth. The contact position and force were also transferred from the multibody dynamics model. The dynamic force validation was also carried out by comparing with some field measurements and good agreement was achieved.

Busquet et al. (2005) reported a quasi-static finite element analysis of the railhead plastic flow due to wheel/rail rolling contacts. The contact force and load distribution was generated via a multibody dynamics model which employed the Hertzian and Kalker (Chollet, 1999) contact theory. The dynamic results were then transferred into the refined 3D solid rail model to calculate the metal plastic flow. No contact surface irregularity was concerned in this research.

With assumption that the contact bodies are rigid, the rigid multibody dynamics has the advantage of simplification of calculation and hence is widely adopted to study the wheel/rail dynamic interactive behaviour. However, because the HCT is employed in the rigid body method, its application to this research is difficult as the material plasticity and discontinuous running surface are involved.

2.5.3. Dynamic wheel/rail contact simulations using finite element method

In recent years, some simplified finite element models have employed beam elements to model the wheel/rail dynamic contact behaviour. In these models the HCT was adopted for the wheel/rail vertical interaction and the rail was modelled with beam elements. Andersson and Hahlberg (1998) studied the wheel rail impact at turnout crossings using a finite element model. Trains were considered as discrete masses, springs and dampers system and Rayleigh-Timoshenko beam elements were employed to simulate the rails and sleepers supported by an elastic foundation without any damping. Hertz contact spring was applied for the rail/wheel interaction. Single wheel, half bogie and full bogie models were set up for comparison. Two key factors for impact force of the crossings, rail flexibility difference and transition irregularity were investigated. The transition irregularity was idealised as a trough shaped beam. Results showed that when the transition irregularity was ignored, an impact force from 30%~50% of static load would be achieved while the impact factor varied from 100%-200% if the irregularity was considered. The contact force increased non-linearly with the increase in train velocity.

Dukkipati and Dong (1999) studied the dip-joint problem employing a discretely supported finite element rail model. Multi-spring contact was adopted as the wheel/rail interaction and the joint was modelled with Timoshenko beam elements. Both wheel set and bogie structure were considered for the vehicle model. The simulation was validated by comparing its dynamic forces with some experimental results. It was found that the mass of the whole wagon system shared by the wheel and rail equivalent mass had a significant influence on the P1 force, while unsprung wheel mass and foundation stiffness affected the P2 force significantly.

Koro et al. (2004) established a dynamic finite element model to investigate the edge effects of rail joint. A modified constitutive relation of Herzian contact spring (Kataoka, 1997) was adopted to model the wheel/rail contact. Timoshenko beam elements were used to model the joint structures including the joint bars. Tie springs were employed to connect the joint bars to the rail supported on a discrete elastic foundation. Special attention was paid to the geometry discontinuity at the concentrated loading position using modified double node Timoshenko beam elements. Gap size and train speed effects on impact force were carefully investigated.

The results showed that for velocities lower than 150Km/h, impact force was sensitive to the gap size while the train speed only had a minor influence.

Wu and Thompson (2004) studied the track non-linear effect for wheel/rail impact analysis. A wheel flat was considered as the impact source and a Hertzian contact spring was employed for the wheel/rail interaction. The track was modelled using a finite element method with beam elements supported by non-linear track foundation. The results showed that the pad stiffness affects the impact amplitude significantly.

The 3D dynamic FE model has been employed recently to investigate the wheel/rail contact behaviour with the development of improved computing capabilities. Wen et al (2005) performed a dynamic elasto-plastic finite element analysis of the standard rail joints containing a gap and joint bars. They employed a coupled implicit-explicit technique that imported the initial steady state implicit solution prior to impact into the explicit solution to determine the impact dynamic process. They have reported that the impact load varies linearly with the static axle load but is largely insensitive to the speed of travel of the wheel. The impact force history presented in their paper exhibited *three peaks*, which were difficult to comprehend given the model allowed for only a single wheel.

Wiest et al. (2006) developed a FE model to study the crossing nose damage due to wheel/rail impact. A dynamic model was established to simulate the wheel passing over the crossing nose. The dynamic behaviour of the wheel was idealised as pure rolling and the rail supporting system was considered as rigid. The cyclic calculation was carried out to study the dynamic response and material flow of the rail nose. A quasi-static sub-model was employed after the dynamic analysis to further study the stress and strain evolution. Two different railhead materials, manganese and composite, were carefully studied for the material plastic flow.

Li et al. (2006) developed a full-scale 3D finite element model for wheel/rail contact dynamic analysis on rail squats. A single wheel and rail were modelled with solid elements and contact elements were used for the contact modelling. The rail squats were studied as the contact surface irregularity, and a two-layer discrete support system was employed as the rail foundation. The dynamic contact force time series matched well with field measurements. Material strength, unsprung mass, traction and braking, sleeper spacing and fastening system property played an important role on the dynamic effect.

2.6. A Hypothesis for the Failure of Australian IRJs

There are two key factors that lead to the failure of IRJs:

i) Wheel/rail contact-impact force

ii) Material ratchetting

The wheel/rail contact-impact force is excited by the IRJ structural/geometry discontinuity. Under severe wheel/rail loading, the material retchetting/fatigue is initiated and causes metal flow on the railhead. The initiation and progression of the failure is considered concentrated on the railhead in the vicinity of end post. It is worth noting that, although the wheel/rail interaction force has components in both the vertical and the horizontal planes, the vertical contact-impact force is believed to play the major role. This failure mechanism of IRJs has been widely acknowledged by Australian practioners. As part of a project to study this failure mechanism of IRJ, this thesis focuses on the investigation of wheel/rail contact/impact forces; the material ratchetting issue is covered in another ongoing PhD thesis, using the impact load and contact pressure obtained from this thesis as the input loading.

The wheel/rail contact impact mechanism hypothesis is shown in Fig. 2.14. Because of the difference in modules between the end post material and steel, as well as their connection (glued or non-glued), structural discontinuity exists. As the wheel approaches the joint, an IRJ running surface discontinuity is momentarily generated which forms a recoverable 'dipped' joint. The wheel then 'flies' over the end post gap and 'lands' on the Rail 2 (see Fig. 2.14) and generates the impact. At the time of impact, the wheel exhibits 'two-point contact' due to the dipped joint.

2.7. Summary

The FE method is widely employed for static wheel/rail contact models. By incorporating the material plasticity and edge effects to the wheel/rail contact behaviour, these models draw a conclusion that at the vicinity of the end post, the Hertz Contact theory (HCT) is not valid to model the wheel/rail interaction in the vicinity of the end post.

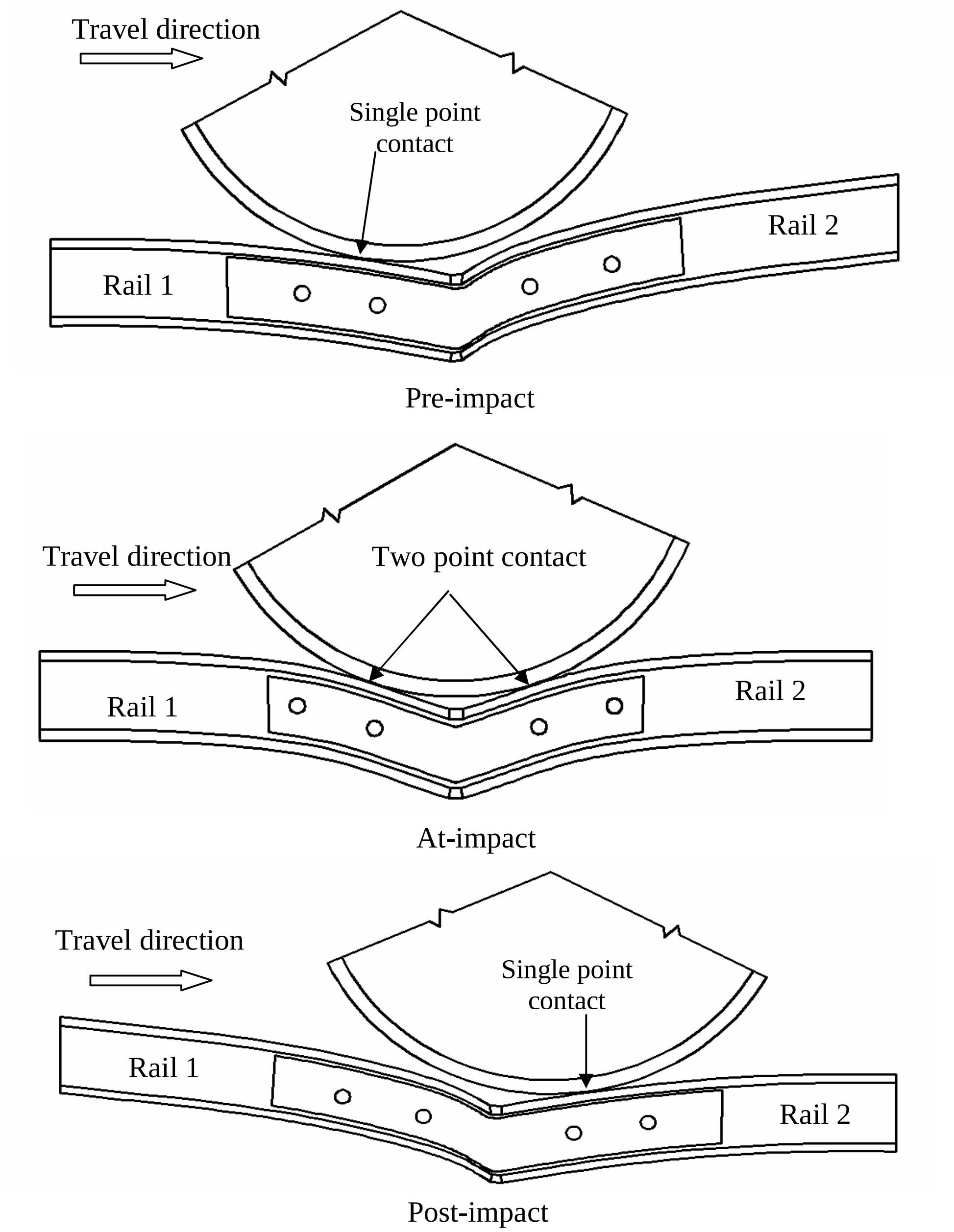


Figure 2.14 Wheel/IRJ contact impact hypothesis

For the dynamic analysis, there are two major methods employed by rail engineering researchers: RMD and FE method. For the conventional RMD models, the wheel/rail vertical contact behaviour is mostly described as ‘single point contact’ and governed by HCT. The structural imperfections of IRJs are usually idealised as surface defects.

This approach is believed to be improper to predict the wheel/rail impacts dominated by ‘multi point contact’ at IRJs. The treatment of IRJ structural discontinuity is also questionable as the ‘new’ IRJs have instantaneous dips under wheel passages but no permanent defects.

With the development of improved computing facilities, the finite element method is increasingly being adopted for 3D wheel/rail dynamic contact modelling at IRJs and other wheel/rail imperfections. The wheel/rail interactions are solved by numerical methods without any assumptions of the contact behaviour as a priori. The capability of modelling the material plasticity and practical mechanical structure makes the FEM the preferred choice for this research.

This chapter has also provided a general review of IRJ designs and failure mechanisms. A hypothesis for railhead failure is presented and relevant literature reviewed.

The theoretical basis for the analysis of contact impact is described in Chapter 3. A FE model for contact-impact analysis of IRJs is developed in Chapter 4 and results provided in Chapter 5.