PAPER • OPEN ACCESS

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To cite this article: A Bracciali and G Megna 2024 *IOP Conf. Ser.: Mater. Sci. Eng.* **1306** 012014

IOP Conf. Series: Materials Science and Engineering 1306 (2024) 012014 doi:10.1088/1757-899X/1306/1/012014

FMEA, monitoring, retrofit and redesign of insulated rail joints

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Abstract. Insulated rail joints (IRJ) are a fundamental component of railway signalling that ensure train protection using "track circuits". A track circuit is a section of line delimited by rail joints electrically insulated, powered at one end with an electric power supply to establish a different voltage that is checked at the other end with a so-called "track circuit relay". When the section is short-circuited by an axle the relay drops, and the section is defined as "occupied". IRJ are subjected to continuous and dangerous failures as they represent a singularity in the rail continuity. Continuous battering produces the classical train impact noise while damage in the rail accumulates until the IRJ fails with extremely unpleasant consequences. The paper discusses the main failure modes of an IRJ starting from a historical perspective, showing how an appropriate failure analysis would have prevented a catastrophic accident that recently occurred in Italy. Several countermeasures are shown and a completely new IRJ potentially completely solving the issue is introduced.

1. Introduction
On January 25th, 2018, a railway accident [1] happened on the outskirts of Milan involving a train coming from Treviglio near the village of Pioltello, causing the death of 3 passengers and major damages to vehicles and infrastructure. The push-pull train consisted of a driving trailer, four passenger cars and a pushing locomotive. It was running at 140 km/h when the first bogie of the third passenger car derailed suddenly over a broken insulated rail joint (IRJ).

Investigations readily discovered that the two rail ends that constitute the joint where were separated by approximately 25 mm and that the downstream rail was heavily battered by the passing wheels. An around 23 cm piece of rail eventually detached, ending under one of the train wheels, producing a "jump" and the consequent derailment. The fragment showed signs of the classical "defect 135 – star crack from fishbolt hole" as described by the UIC 712 code, that is probably the most common critical and symptomatic defect that regularly affects bolted joints.

2. Brief IRJ description
An insulated railway joint guarantees both the rail mechanical continuity to support the loads of the trains passing on the line and the electrical insulation for separating trains and protecting them from collisions with the "track circuit" system. As it will be shown in this paper, these requirements conflicted at least in the Pioltello accident. Insulated rail joints are made by several different parts

made of different materials. The following description applies to prefabricated IRJ, the most common type, that are inserted in the track by welding the IRJ to existing rails.

Figure 1. The joint broken in Pioltello on 25.01.2018. The train travels right to left. It can be seen that downstream portion of the IRJ is completely destroyed. The flown away portion of the railhead got stuck under a wheel causing the derailment of the train.

Two rail bars of length varying in a wide range (approx. from 1.5 to 12 m) are cut, deburred and their web is drilled with 2, 3 or 4 holes (called "fishbolt holes") to result in an IRJ with 4, 6 or 8 holes. The rails are then connected by using two steel profiles (called "fishplates") fastened to the rail by using either conventional bolts (called "fishbolts") or hydraulically pulled irreversible locking bolts (like rivets). Insulating sheets made of fiberglass guarantee the electrical insulation between the fishplates and the rails as well as the insulation between the fishbolts and the fishbolt holes. An "end post" around 5 mm thick between the rail ends completes the insulation.

An IRJ is assembled by bonding all the components with a high-strength structural epoxy glue to provide the requested mechanical strength as friction would not result to be sufficient to prevent longitudinal displacements under large axial forces arising from the thermal behavior of an ordinary CWR (Continuous Welded Rail) track. After an appropriate curing time (2 to 4 weeks) the assembled IRJ is delivered to the application point.

3. Design and criticalities in conventional IRJ

3.1. Historical background

The extensive use of IRJ dates to the massive introduction in early XXth century of track circuits to guarantee train protection. At that time the use of relatively short, jointed rails was common (typically 18 m long) as the development of currently used rail welding processes (aluminothermic and flash butt) was still in progress. The IRJ were assembled with a specific kit directly on track without gluing them.

With the adoption of CWR (Continuous Welded Rail), the IRJ strength was increased by bonding all the elements. As this process revealed to be critical on the track, IRJ were started to be assembled in a plant and the "prefabricated joint" was delivered to the desired location and welded to the existing track with special attention to keep the desired stress state of the rail if temperature is not close to the SFT (stress-free temperature) of the rail.

The drawing of IRJ may date back to the 60s. Small modifications may have been introduced in materials and or in the sequence of operations but basically the design remained the same. The drawing in figure 2 shows the original prefabricated joint that was introduced in Italy in 1968. The current drawing is very similar, the only difference being the replacement of C960 fishbolt with Huck bolts.

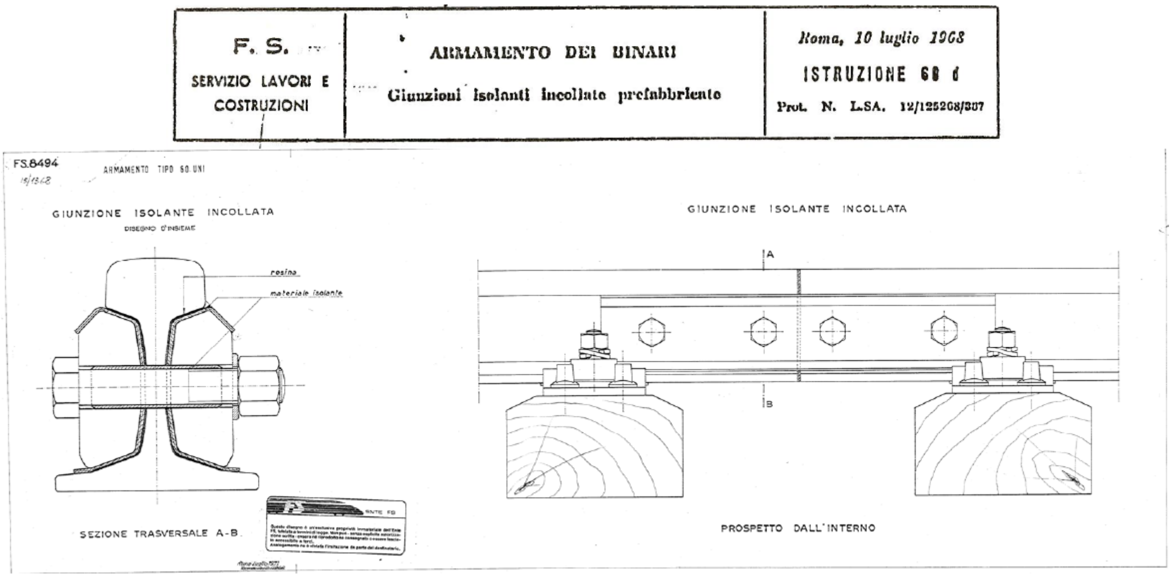

Figure 2. Reproduction of the drawing of the standard prefabricated IRJ in Italy since 1968.

Figure 3. The IRJ currently used in Italy pictured before installation. A specifically widened sleepers was developed to (theoretically) better support the IRJ. Hollow sleepers to pass cables can be seen. Sleeper spacing is adjusted during installation but results to be non-standard with tamping difficulties.

3.2. FMEA of IRJ and criticality analysis

Failure Mode and Effects Analysis (FMEA) is the process of reviewing as many components, assemblies, and subsystems as possible to identify potential failure modes in a system and their causes and effects [2]. While procedures for conducting FMECA (Failure Mode, Effects and Criticality Analysis) were described in US Armed Forces Military Procedures document MIL-P-1629 in 1949, no such analyses were common practice in the railway environment until recent times. IRJ were not certainly analyzed in a formally planned FMEA framework. No trace of such analyses was found in the literature and, what's more, no design calculations or test results were found about conventional, old IRJ.

Although a full FMEA according to nowadays approach was performed, a more conventional analysis of failure modes and their consequences can be conducted by using engineering judgment and the experience arising from more that one century of use of IRJ throughout the world.

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Unfortunately, IRJ failure is relatively common and descends basically from the interaction between the (loaded) wheels and a rail with important stiffness variations along its length, generating a “dip joint” irregularity. The shocks given by wheels passing over the discontinuity (gap) between the rails result in rail steel flowing, high stresses in the fishbolt holes, high stresses in the fishplates [3-5].

Mechanical FMEA of IRJ leads to the following failure modes:

- debonding of the joint under the combined action of high pulling forces due to thermal actions of the CWR in cold season and the aforementioned shocks;
- failure of the rail cross section with 45°-oriented cracks originating from fishbolt holes (so-called “star cracks”), due to both the stress rising given by holes (worsened by bad drilling and/or absence of hole deburring) and the aforementioned shocks;
- failure of the fishplates for high stresses when IRJ support (ballast) has lost its bearing capability (worsened by the fact that IRJ can hardly be tamped because of the presence of cables on the track), enhanced by the aforementioned shocks;
- failure of the fishbolts when the axial displacements of a debonded IRJ is such that the design clearance between the fishbolts is recovered and the fishbolt is sheared instead of simply pulled. Crack propagation is speeded up by the aforementioned shocks.

It should be noted that while some of these failures are consequential to the joint debonding (e.g. bolts shearing), some others are independent (e.g. star cracks and fishplates failures). A common root cause for all the failures can be easily identified in the shocks naturally occurring in the IRJ because of the unavoidable endpost gap.

Criticality analysis needs little explanation considering the consequences of the disaster described above. All literature considers the debonded joint (the only easily degraded condition observable with the naked eye) to be replaced in the shortest possible time with temporary speed restrictions until the replacement,

Electrical FMEA of IRJ leads to the following failure modes:

- loss of rail insulation due to fiberglass crushing in the fishbolt holes, possible only if the IRJ is debonded and already seriously malfunctioning;
- loss of insulation on the rail head due to “lipping” of rail ends because of repeated plastic deformation of steel that brings the rails in contact;
- loss of insulation of fishplates insulation (rare).

It must be underlined that loss of insulation has a negative impact on service regularity (the track circuits resulting “occupied” stopping train circulation) but leads to a safe condition as the “electrically broken” IRJ prevents any derailment. It can be said that from this point of view the IRJ is “self-protecting”, and that the failure mode is not critical as it leads to the typical *fail-safe* condition.

It is worth mentioning a safety-related condition non directly regarding the IRJ itself. Conventional track circuits have the intrinsic capability to detected broken rails as the track relay drops if the track circuit is opened. With axle counting block or radio block systems there is no need for IRJ anymore, but the continuous check of the overall integrity (continuity) of the track is lost.

3.3. Considerations about certification process of conventional IRJ

As rails are welded today and CWR approach is extensively used throughout the world, joints remain as a signaling-related component only. The safety analysis of any modification (new technology or improvement) to an existing railway system must follow a so-called *Common Safety Method (CSM)*, that in Europe is formalized by the Regulation 402 of EU.

The application of such method starts from a preliminary analysis of the modification proposed; if it is deemed to relevant, a formal risk assessment process must be strictly followed under the supervision of third-party competent assessor.

Signaling components belong to control-command systems. The are described in a Technical Specification for Interoperability of the European Union (TSI-CCS). Basically, CCS components are classified according to the SIL (*Safety Integrity Level*) of the application, that can be shortly defined as the level of reliability that the CCS system must guarantee during service.

As for the FMEA described above, none of these formalities were present decades ago, and all IRJ were internally approved by national railways.

4. Root cause of the Pioltello accident

It was said previously that the train derailment was originated by the interaction of a trail wheel with a slice of rail section that detached from the downstream portion of the joint.

Starting from this evidence, a possible reverse sequence of the events is likely the following:

- star cracks appeared starting from the downstream hole close to endpost, and cracks progressed until the rail slice detached;
- as observed, the rails displaced by more than 20 mm, so debonding was a clear contributor to the final failure;
- during the movement the fishbolts certainly crushed the small fiberglass tubes insulating them from the fishplates and the rail web.

This last condition conflicts with the expected (and declared above) *fail-safe* condition guaranteed by an IRJ, i.e. the loss of insulation (and the consequential interruption of train circulation) of the joint. What happened may be explained by figure 4.

Figure 4a shows the conventional joint as assembled in a plant, tested and correctly installed on a railway line. Track circuits power supply and insulation element geometry are such that rails facing in the IRJ are at different electrical voltage (red and yellow). The fishplates are neutral, as they are insulated from both the rails and the fishbolts.

Figure 4b describes what happened in Pioltello. The left (yellow) rail displaced by a large distance (more than 20 mm) destroying both fishbolts/rails and fishbolts/fishplates tubes. As a result, both fishplates "became yellow", therefore getting the same electrical potential as the left rail. This condition stayed for a long time until the whole joint was destroyed without losing its insulation and therefore without shortening the track circuit. **This is the root cause of the Pioltello accident: the missed track circuit occupation given by an IRJ that was mechanically destroyed**.

A short redesign scenario was then approached that readily showed that there are several possible insulation arrangements that fulfil the requested condition "mechanical failure → electrical failure → interruption of service → no risks". Figure 4c shows a possible layout in which:

a) each rail in electrically connected to one of the fishplates and
b) fishbolts are insulated only on one side by an insulated washer (no fiberglass tubes)

It can be easily proven that any movement of any component immediately leads to short-circuiting the rails, causing the immediate stop of the traffic along the life. This is a *fail-safe* condition reached by a simplified FMEA.

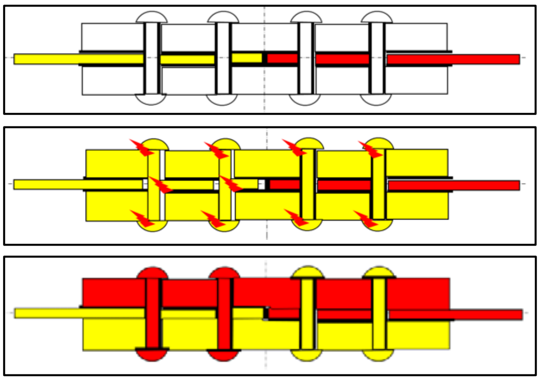

Figure 4a. Horizontal cross section of an IRJ in standard conditions.

Figure 4b. Horizontal cross section of an IRJ when the left rail moved to the left bringing the fishbolts in contact with the rail web and the fishplates.

Figure 4c. Horizontal cross section of a modified IRJ in standard condition. Any movement leads to short circuiting the rails.

5. In-service check and improvements of existing joints

5.1. Measurement of the endpost gap

Several commercial devices were developed in Italy before and after the Pioltello accident [6,7]. They are basically designed on the principle of checking any increase in the endpost gap design (5 mm) by using either mechanical, electromechanical, or optical sensors (figure 5).

Figure 5. Left: electromechanical IRJ found detached along a railway line (photo A. Bracciali). Right: optical IRJ sensor (from [6]).

One of these designs was extensively used showing some limitations:

- the sensor is applied in the IRJ manufacturing plant but tends to be detached during handling of the joint during the trackworks;
- On-Track Machines (OTMs) with rubber tyres used during trackworks interfere with the bonded sensor, further detaching it;
- no connection to the signalling system was provided until today, making the check nearly useless (one type of device has just a mechanical device that is redundant as IRJ opening can easily be checked visually).

It must be stressed that this kind of device is unique of Italy and, to the best knowledge of the authors, is not used elsewhere. None of these devices leads automatically to an increased safety, as the relevant data (endpost gap) must be measured, transmitted, processed and the relevant actions must be taken to ensure that the adequate level of safety is achieved, and all these steps must comply with the aforementioned regulations on signaling systems.

5.2. Addition of an intrinsically safe switch

A different approach to intrinsic safety was proposed by the authors taking inspiration from the past practice of short-circuiting the rails when many yards were electrified. As shown in figure 6, a rather common practice was to weld conductive cables to the field side of railheads to ensure the return of current to electric substations. Similarly to this design, a pair of stainless steel elements forming a switch was developed. The use of conductive glue was forecasted to avoid welding that is not accepted anymore in main line applications.

Beyond the greatest advantage of simplicity of manufacturing and installation and a ridiculous cost, the main advantage of this device is that it automatically stops traffic when the IRJ debonds, ensuring the highest possible safety. A formal FMEA analysis was not conducted because of the simplicity of the device and because the proposal was not even considered by the railway industry.

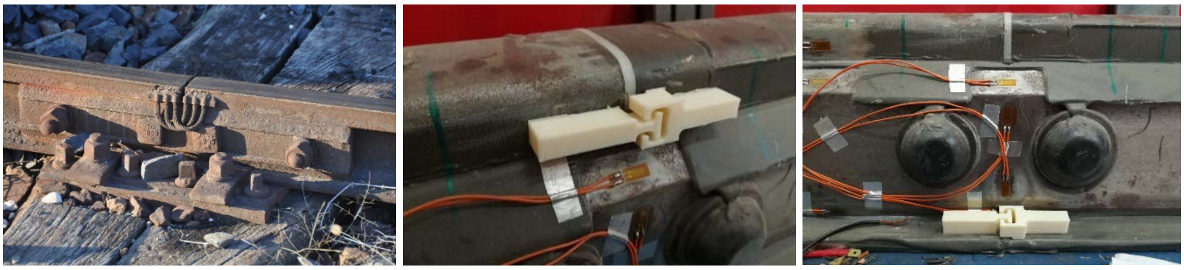

Figure 6. Left: current return conductors in an electrified yard with old rails resting on wooden sleepers (photo A. Bracciali). Safety switch produced with rapid prototyping technique bonded to field side of railheads (centre) and to rail bottom (right).

6. Introduction of a new IRJ to remove all failures

According to the FMEA conducted on existing IRJ, the common mode of failure with direct and potentially immediate effects on safety is debonding. If debonding doesn't appear other failures may appear (e.g., nucleation of cracks in fishbolt holes) but with possibly lower occurrence and effects. Other failures, such as rail lipping or burring, can be removed restoring the joint operation without safety implications.

Debonding certainly happens because of tensile forces in cold seasons although qualification tests require that IRJ must withstand a tensile force of 1500 kN or even 2000 kN. Even though this value may be unrealistically too high, IRJ debond *because of impacts*. The only way to avoid any joint failure in principle is *removing the shocks*.

This evidence is at the basis of the development of a (patented) completely new IRJ obtained by coupling two shallow depth switch rails properly machined with a lower thick plate (joint cover) and proper insulating components. While the joint is described thoroughly on the website www.absolutelybetterjoint.com and on the paper [8] to which the reader is referred, the concept is quite simple: using an shallow cut (3°) of thick web rails to increase the "handover" length up to 400 mm completely avoiding shocks. While this type of joints was attempted in the past by using thick web rails for expansion joints, the innovation introduced by the lower plate enormously increases bending strength while the geometry is fully compatible with existing tracks with standard sleepers (figure 7)

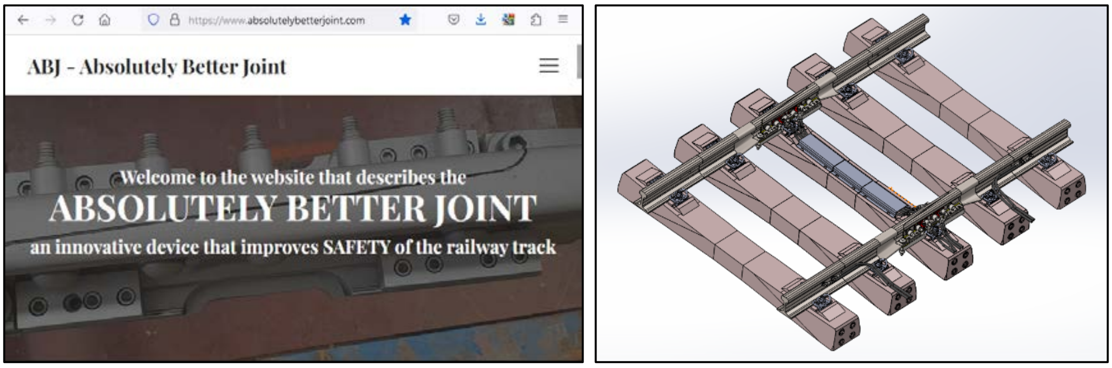

Figure 7. Left: home page of the *Absolutely Better Joint* (ABJ) website. Right: General view of a track jointed with ABJ (note cabling that allows continuous tamping and the unchanged sleeper type and spacing)

7. Conclusions and further developments

Insulated rail joints are still a source of headaches for infrastructure managers. Despite the use of several technique to reduce the failure rate, such as the increase of the number of fishbolts, the increase in the length of the fishplates and the use of *cold bolt expansion* technique to reduce star cracks from fishbolt holes, IRJ remain an Achille's heel in a heavily loaded railway track, without mentioning the impact noise always present also in IRJ in mint conditions.

FMEA analysis showed that one the most critical accident arising from a broken IRJ was due to the lack of consideration of the criticality of a failure mode. Some devices to monitor existing joints were described, together with a simple retrofit safety switch that could avoid in principle accidents of the kind.

But the most important innovation is the introduction of a new joint (called ABJ) that generates no shocks at all. As shocks are the root cause of all damages, this new joint promises to be very effective in removing forever the issues related to conventional IRJ use. Currently a first batch of ABJ joints is in production to make official homologation tests. Line tests are expected to start by 1Q of 2024.

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