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Review of failure analysis of coupling systems on trains

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Abstract

This paper provides a comprehensive examination of the failure analysis of screw couplings and draw gears in trains across Europe and other countries where screw coupling systems are still used. The analysis of these failures reveals distinct characteristics, allowing for categorization of these failures into recurring patterns observed on other railways. The presence of various failure types indicates that multiple factors contribute to the occurrence of coupling system breaks, and these factors are not uniformly distributed. Many studies on failure analysis focus on investigating the fatigue of screw coupling and draw gear components through a combination of experimental tests and numerical analyses employing the finite element method. Apart from initial cracks and corrosion, some fractured elements do not exhibit signs of fatigue, necessitating consideration of other potential causes in the analysis. These causes may include overload, impact, inadequate material, or deficiencies in the heat treatment of fractured elements.

Keywords: Railway; Coupling system; Screw coupling; Failure; Draw gear

1. Introduction

This paper discusses system used between railway vehicles in Europe, which is made up of draw gear and screw coupling. They are responsible for transmitting traction and tensile forces between railway vehicles and the locomotive. According to Development of a concept for the EU-wide migration to a digital automatic coupling system (DAC) for rail freight transportation (2020), automatic coupling systems are employed worldwide, except in Europe

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and some African countries (Fig. 1). As coupling systems provide the mechanical connection of wagons in trains and aim to enhance efficiency in railway transport, automatic couplings have been used globally for over a century. In Europe, the standard screw coupling requires manual operations for coupling and uncoupling, which have been physically demanding, hazardous, and inefficient given the new requirements for competitive transport.

In this paper, only failures of standard screw coupling and draw gears were considered. Screw coupling elements are designed to fail before the draw gear and have maximum breaking loads lower than the draw gear. They are made of forged steel and generally have a lifespan of approximately 30 years unless exceptional circumstances arise. However, due to the dynamic loads experienced by railway vehicles, fatigue failure of screw couplings can be expected. In severe cases, significant forces can lead to train breaks apart, reducing the safety of railway traffic. When train breaks occur, the separated parts are automatically braked, and stopped, and there have been no reported casualties or substantial costs associated with such incidents.

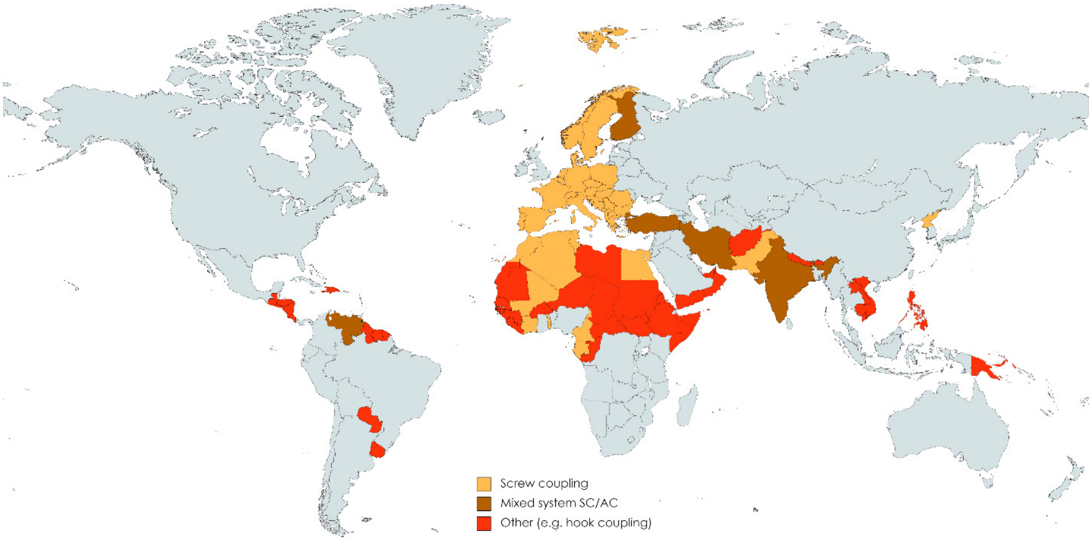

Fig. 1. Coupling systems in the world

2. Case studies of coupling system failures

There are not many studies in scientific circles dedicated to the examination of screw coupling and draw gear failure. The application of recommended UIC and EN regulations (UIC 520,UIC 825, UIC 826, EN15566), which have set strict requirements for the design, control, and technical conditions for the delivery of screw coupling, could suggest that these systems have no frequent failures during operation. The long-standing record of incidents maintained by the national undertaker in freight transport in Serbia shows otherwise. Additionally, several published studies in this field in recent years indicate that other railway operators in Europe also have failures of screw coupling and draw gear elements. The purpose of this paper is to conduct a thorough examination of documented incidents of coupling system failure to identify patterns or underlying causes that contribute to these events. The ultimate goal is to minimize the occurrence of such incidents. The failures shown in analyses carried out on European railways occur at critical points of the coupling system and are present in the failures on the Serbian railway. An overview of the most common failures with the appearance of fractures on Serbian railways is shown in Fig. 2.

2.1. UK, Camden Road Tunnel, 2007

According to Rail Accident Report: Runaway of two wagons from Camden Road Tunnel 19 July 2007 (2008), the train was stopped at a signal, by the driver using the service brake. When the signal cleared, the train started. However, after moving about 8 meters, the screw coupling between the 2nd and 3rd wagons from the back of the train broke.

The train consisted of a locomotive and 28 wagons loaded with stone, connected by a combination of screw couplings and instanter couplings. The driver did not check to ensure that the train was correctly connected, and closed the cocks on the end vehicle before driving away. Two wagons were left unnoticed in Camden Road Tunnel and due to brake defects, they rolled backwards in the opposite direction for 200 to 300 meters on a downhill gradient. A similar incident occurred near East Didsbury on August 27, 2006, when detached wagons ran backwards for around 4.8 kilometres through an engineer's work site following the failure of a coupling (fracture of draw hook of instanter coupling).

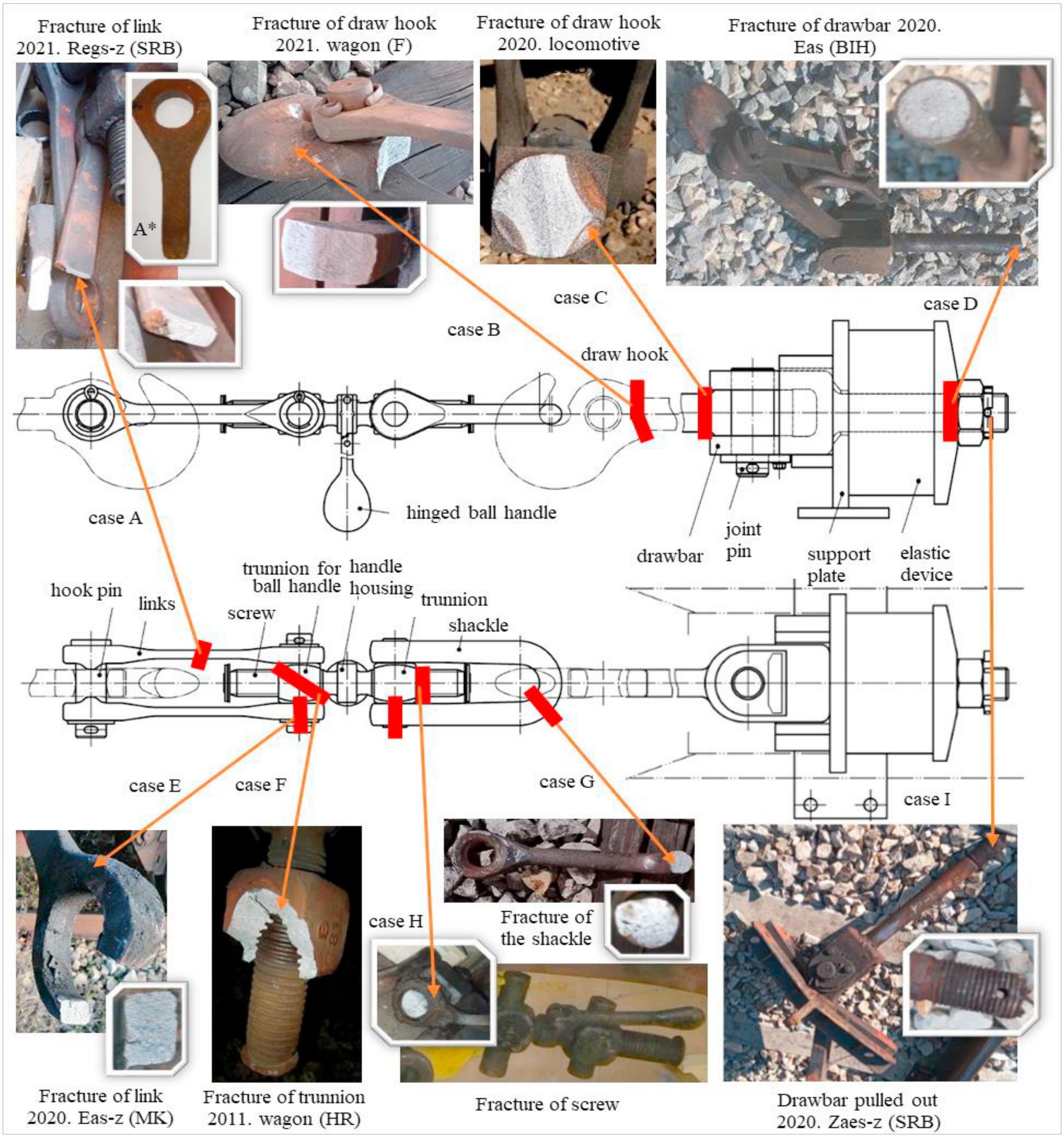

Fig. 2. Failures of coupling system with the appearance of fractures on Serbian railway

The incident in Camden Road Tunnel was caused by a broken eye of a shackle. Examination of the broken eye revealed that one side of the eye fractured rapidly with a brittle structure, while the other fracture was a rapid ductile failure. No evidence of fatigue was found. The brittle fracture suggested that the material in that part of the eye had been subjected to localized heating and cooling some time after manufacture. The hardness measured (more than 600HV30) was beyond that, specified for the coupling (255 – 305HV). The hardness of the ductile fracture was found to be within the specification for the type of steel used in the manufacture of the coupling. The Rail Accident Investigation Branch concluded that the brittle fracture occurred first based on the results of the metallurgical examination. It appeared from the amount of wear that the coupling had been in service for some time, although the maintenance records showed that both couplings were renewed three years ago.

Between 1997 and 2007, there was a reduction in train divisions from 102 to 33 occurrences, due to all causes (not divided by type of coupling). This reduction corresponded with a decrease in the number of coal wagons fitted with instanter coupling. According to the analysis of English, Welsh & Scottish Railways, most train divisions occur either within the first few wagons close to the locomotive, or within the rear few wagons.

2.2. Slovakia, heavy freight train

In Slovakia, a heavy freight train experienced a failure when it accelerated after stopping at a signal during winter. The exact circumstances that led to the fracture of the locomotive draw hook are not available. According to Novy et al. (2019), the brittle fracture was caused by a combination of factors. The material properties of the draw hooks used in Slovakia are prescribed by a national standard from 1979, which has not been significantly revised to date. The standard prescribes minimal values for impact toughness at +20°C but does not provide values for lower temperatures, which can drop to -20°C in central Europe.

The fracture occurred in the root of the transition radius on the bottom side of the draw hook and exhibited a fully brittle character without any signs of fatigue (similar to fracture in Fig. 2 case B). Although the chemical analysis of the draw hook met the requirements of the standard, microstructural observation revealed a coarse pearlitic-ferritic microstructure that reduced ductility and toughness due to inappropriate heat treatment during manufacturing. The mechanical properties of the draw hook did not meet the requirements, and the impact toughness decreased significantly at lower temperatures. The influence of the coarse-grained structure caused insufficient mechanical characteristics of the material and decreased toughness at lower temperatures.

The loading of the draw hook was simulated using FEM with an additional load component to simulate non-coaxial loading, which resulted from the different heights of the draw hook axis of the locomotive and wagon. Non-coaxial loading significantly increased the peak values of stress in the transition radius of the draw hook. The change in the cross-section of the hook at the transition point from the neck to the head led to an increase in stress concentration.

The superimposition of insufficient material toughness, errors in heat treatment, and non-coaxial placement of the draw hook axis, which initiated additional loading, has been a long-standing problem with more than ten cases of draw hook failure per year only in Slovakia.

2.1. Serbia, Pančevo station, 2020

The circumstances of the coupling links failure on a train at Pančevo station in 2020 are obscure. The train composition consisted of 20 Eaos wagons operated by RCH Hungarian Railways, loaded with ore. During the failure, one of the coupling links on the eleventh freight wagon Eaos broke due to a brittle fracture (B sample). The temperature at the time of breaking was +1°C, which eliminates the possibility of an increase in material brittleness. A part of the links cross-section with a changed colour indicated corrosion (similar to fracture in Fig. 2 case A). There were no signs of fatigue of the material.

The study also analysed the failure of coupling links due to ductile fracture (A sample - similar to fracture in Fig. 2 case A*), with very little information about their origin. According to Vukšić Popović et al. (2021), metallography showed that the B sample was hardened and tempered with typical tempered martensite microstructure while the A was normalized with a ferrite-pearlite microstructure. The results of chemical analysis and the mechanical properties of specimens met standard requirements. The fracture surface of sample A showed elongation of the link, narrowing of the cross-section and the formation of a neck before fracture, typical of ductile fracture. The symmetrical shape of the fracture indicated that there was no stress concentration, and a visible reduction in the cross-section indicated high plastic deformations resulting from tensile overload. Sample B showed no visible plastic deformation, and the fracture surface had noticeable traces of crack growth in the form of well-known chevron lines typical for brittle transcrystalline fracture.

The FEM analysis of the links was used based on the mechanical properties obtained by standard tensile testing for both samples. As the stress value obtained in the model is within the prescribed tensile strength range, it means that the coupling link will break at the minimum breaking force (425 kN). The stress values due to the working load are at the limit of the yield stress and for the minimum breaking force at the limit of the tensile strength of the link. This indicates that when overloaded by the axial tensile force of the traction device, plastic deformation or breaking of the links would occur. Therefore, the FEM analysis confirms that the failure of the coupling links can be attributed to operational loads surpassing the permissible limits.

2.2. Slovakia, the fast passenger train

Material fatigue was identified as the main cause of failure, supported by Ulewicz et al.'s (2019) findings using the finite element method (FEM). They revealed that the failure occurred due to a combination of factors, including operational conditions, deviation of the draw hook geometry from the prescribed specifications, and unforeseen additional loads.

The draw-hook on the passenger wagon of the high-speed train operated by the Slovak state railways failed, causing the train to separate between two stations. The chemical composition of the draw-hook was comply with the standards, showing no significant deviation from the prescribed composition for the steel grade 47 Mn. The microstructure of the draw-hook, characterized by a fine-grained pearlitic-ferritic structure, indicated that the forging process and subsequent heat treatment were performed correctly. The draw hook met all the required mechanical properties as specified in the standard.

Upon inspection of the broken draw hook, it was evident that the failure was due to fatigue. Fatigue cracks primarily originated from four symmetrically distributed locations in the transition region where the rectangular cross-section changed to a cylindrical shape (similar to the fracture in Fig. 2 case C). The fatigue cracks exhibited rapid growth from the bottom side. The transition radius of the draw hook had a significantly smaller value than prescribed, resulting in a high-stress concentration at its root, making it prone to the initiation of fatigue cracks and leading to premature failure.

The upper part of the draw-hook body showed heavy wear caused by substantial friction in the contact area of the linear casing. This friction was a consequence of the significant difference in wheel diameters between the neighbouring wagon, which also subjected the draw hook to additional bending loads. Furthermore, the draw-hook was not aligned coaxially with the draw-hook assembly, but acted at a certain angle. The results of the FEM analysis indicated significantly higher stresses in the case of the actual radius and additional bending loads (449 MPa) compared to the case of clear tension with the correct radius (291 MPa).

2.3. Romania, passenger train

The analysis of a damaged coupling link (similar to fracture on Fig. 2 case A) on a passenger wagon was conducted without having the basic information regarding the causes of failure. Due to this lack of information, the analysis relies heavily on assumptions. In the analysis of screw coupling failure Cernescu et al. (2013) determined the defect of the material that led to the initial crack.

There are differences between the chemical composition and mechanical properties of the tested material and the materials specified in UIC standards for coupling links. The chemical composition of the link indicates low carbon steel and the mechanical properties are likely higher than usual due to the heat treatment. Through micrographic analysis, the fracture surface was divided into three regions, and for each region, a size limit and an average distance between striations were estimated. Fatigue lines can be observed on the fracture surface of the coupling, providing a basis for estimating the propagation of the initial crack due to material fatigue.

Based on the experimentally determined characteristics of the material, the coupling system in the train was modelled as a longitudinal system. This model was represented by differential equations and calculated the values for traction forces on the screw couplings along the train composition, corresponding to the adopted representative acceleration from 0 to 60 km/h. Tensile tests were performed on a screw coupling from the same batch as the failed link to determine the proportionality constant of the screw coupling. Using the determined load (approximately 229 kN), the coupling link was numerically modelled using the Finite Element Method (FEM).

The results of the FEM analysis indicate that both the stress and strain states of the coupling link material are within acceptable limits of strength and stiffness. The area with the highest concentration of normal stress is the lateral edge of the link's cross-section, where the crack was initiated. The maximum values of normal stress on the cross-section of the damaged link correspond to the maximum values for the first five couplings in the train.

By utilizing the Franc 3D program package for assessing crack growth, it was estimated that the number of cycles leading to the failure of the hanger was approximately 6474 cycles, which, under the analyzed conditions, corresponds to one month of vehicle operation.

2.4. Other cases of coupling system failures

Analysis by non-destructive methods of draw hook, by Mohammadi et al. (2019), showed initial cracks at the critical points where the clutch stirrup is placed, and determined material fatigue as the primary factor of draw hook failure. The test was performed on a reduced model of the draw hook. The life span of the draw hook was determined by simulation depending on the place of load input in operation, which was considered in two characteristic cases: when the draw hook is attached to the neighboring wagon via a classic or central coupling.

Upon examining instances of fractures, it is evident that some elements of screw coupling and draw gear are more susceptible to failure. Also, according to the EN 15566 (2016) and UIC 826 (2004) regulations, the safety component of the screw coupling that should break under overload was the screw before 1995, and after reconstructed link. Regulations vary in different countries and over time, resulting in diverse characteristics of elements in operation, since the expected lifespan of screw coupling and draw gear is 30 years. Furthermore, specific operational conditions, variations in load size and frequency throughout the lifespan, contribute to the complexity of the analysis.

The systematisation of screw coupling and draw gear failure analysis show the following characteristic cases:

- Fractures of the drawbar, which typically transpire at the start of the thread, leading to the separation of draw gear components and causing damage to the guide and support plate on the wagon (Fig. 2, case D).
- Fracture of the drawbar or detachment of the nut resulting in the separation of draw gear elements and damage to the guide and support plate on the wagon (Fig. 2, case I).
- Fractures of the coupling link, commonly at the midpoint of its length (Fig. 2, case A) or at the eye of the hook pin or trunnion (Fig. 2, case E).
- Fractures of the draw hook at the change in cross-section (Fig. 2, case C), at the transition from neck to the head (Fig. 2, case B), or at the connection with the hook pin.
- Detachment of the hook pin or joint pin, caused by detachment or fracture of the split pin, resulting in separation of the draw hook.
- Fractures of the trunnion, screw or shackle (Fig. 2, case F and H), resulting in separation of the screw coupling.

Fractures in screw coupling and draw gear elements can arise from material fatigue, usually at stress concentration. Additionally factors such as severe corrosion, material defects during production, or initial cracks or external damages acting as stress concentration points during operation contribute to these fractures. The mentioned fractures encompass cases with brittle fractures (with or without signs of corrosion or material fatigue) and fatigue fractures.

Train breaks apart take place upon a failure of screw coupling or draw gear elements. Additionally, train breaks apart can occur when there are failures of air brake components (brake hose, valve, pipe etc.). The average number of train breaks apart on Serbian railways for freight railway transport of national undertaker "Serbia Cargo" from 2018 to 2020 was 36,4 per year. According to Vukšić Popović (2021) from 2018 to 2020 at "Serbia Cargo", screw coupling elements failed in 21% of train breaks apart, while draw gear elements failed in 54% (Fig. 3). As the screw and coupling link serve as safety elements of the coupling system and are expected to fail before others, their failure rate should be higher.

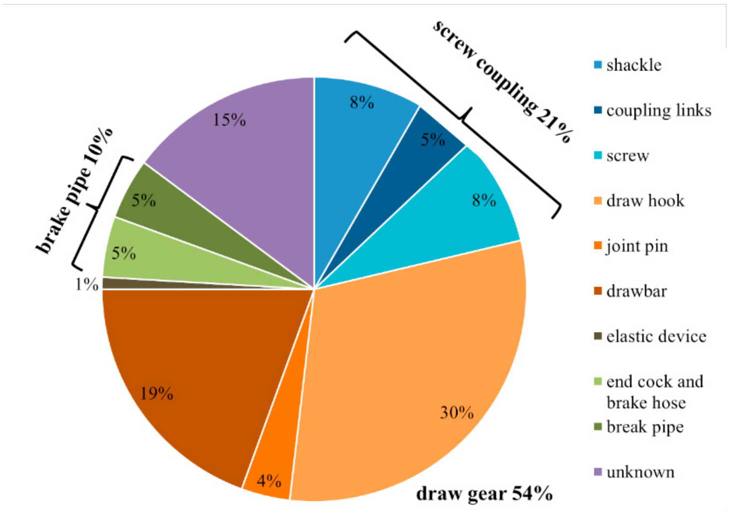

Fig. 3. Distribution of failures in coupling system components

3. Conclusion

The following safety recommendations regarding coupling system failure have been proposed:

- Rail Accident Report: Runaway of two wagons from Camden Road Tunnel 19 July 2007. (2008): EWS should establish a process to educate its maintenance staff about avoiding the application of heat to forged components like couplings to prevent degradation of material properties. Additionally, EWS should implement a monitoring system to track incidents of coupling failures based on coupling types. Furthermore, EWS should introduce an analysis system to investigate coupling failures specific to each coupling type and take necessary measures to reduce instances of train divisions caused by particular couplings.
- Novy et al. (2019) suggest modifying the testing methods and conditions stated in the standard to ensure safe operation across a wide range of operating conditions.
- Vukšić Popović et al. (2021) recommend conducting more detailed analyses of draw gear and screw coupling fracture, and monitoring of trains composition and the operational condition of couplings.
- Ulewicz et al. (2019) propose that in order to prevent similar failures in the future, it is essential to redefine the relevant standards and strictly adhere to regulations regarding operating conditions.
- Cernescu et al. (2013) suggest that the increased loading of coupling systems, combined with additional shocks and potential structural defects, highlights the need for initiating a program to verify these systems and improve the testing methodology for couplings.

Upon analyzing the causes of failure in screw coupling and draw gear elements, we can categorize them as follows:

- Fatigue fractures: These occur due to material failure at locations of stress concentration, with or without signs of corrosion. Examples include fractures at the cross-section change of the draw hook (Fig. 2, case C).
- Brittle fractures resulting from corrosion: In these cases, surface damage combined with corrosion and variable cyclic loads leads to the spread of corrosion across the cross-section, without apparent signs of stress concentration. An example is the breakage of the coupling link (Fig. 2, case A).
- Brittle fractures originating from initial cracks or surface damage: These fractures initiate from specific points and propagate along visible lines. Examples include fractures of the drawbar (Fig. 2, case D), the draw hook at the cross-section change (Fig. 2, case B), trunnion fractures (Fig. 2, case F), and coupling link fractures (Fig. 2, case E).
- Ductile fractures: In these cases, there is a clear narrowing of the cross-section before the fracture occurs. An example is the fracture of the coupling link (Fig. 2, case A*).

The presence of these various types of fractures indicates that multiple factors contribute to the failures of screw coupling and draw gear elements. It is known that ductile materials can experience brittle fractures under certain conditions such as low temperatures, high deformation rates, stress concentration, corrosion etc. However, the analysis conducted by Vukšić Popović (2021) regarding the distribution of fractures by month did not reveal a connection with low temperatures. Corrosion, in combination with tensile stress, can also cause brittle fractures in ductile materials, even at stress levels lower than the yield stress.

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References

Development of a concept for the EU-wide migration to a digital automatic coupling system (DAC) for rail freight transportation, 2020. Final Report for the Federal Ministry of Transport and Digital Infrastructure (BMVI), hwh Gesellschaft für Transportund Unternehmensberatung mbH, Germany

Rail Accident Report: Runaway of two wagons from Camden Road Tunnel 19 July 2007, 2008. Rail Accident Investigation Branch, Department for Transport, UK,

Cernescu, A., Dumitru, I., Faur, N., Branzei ,N., Bogdan, R., 2013. The analysis of a damaged component from the connection system of the wagons, Engineering Failure Analysis 29, pp. 93–107.

Vukšić Popović, M., Tanasković, J., Glišić, D., Radović, N., Franklin, F., 2021. Experimental and numerical research on the failure of railway vehicles coupling links, Engineering Failure Analysis 127, 105497

Ulewicz, R., Nový, F., Novák, P., Palček, P., 2019. The investigation of the fatigue failure of passenger carriage drawhook, Engineering Failure Analysis 104, pp. 609–616.

Nový, F., Jambor, M., Petrů, M., Trško, L., Fintová, S., Bokůvka, O., 2019. Investigation of the brittle fracture of the locomotive draw hook, Engineering Failure Analysis 105, pp. 305–312.

Mohammadi, M., Rahmatfam, A., Zehsaz, M., Hassanifard, S, 2019. Failure analysis study of railway draw-hook coupler, Journal of Central South University 26, pp. 916–924.

Vukšić Popović, M., 2021. Failure analysis of draw gear and screw coupling of railway vehicles as a factor of safety and trains break risk, Ph.D. thesis, University of Belgrade Faculty of Mechanical Engineering

UIC 520 Wagons, coaches and vans — Draw gear — Standardisation

EN 15566:2016 Railway applications - Railway Rolling stock - Draw gear and screw coupling, 2016.

UIC 825 Technical specification for the supply of draw hooks with nominal load equal to 250 kN, 600 kN or 1000 kN for tractive and trailing stock

UIC 826 Technical specification for the supply of screw couplings for tractive and trailing stock, 2004.