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Fatigue damage leads to a serious traffic accident

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Abstract

The engineering forensic analysis of a traffic accident involving a truck and a bus is presented. Fractographic, metallographic and mechanical studies and numerical models of load transfer and crack propagation were made. A mechanical failure due to fatigue crack propagation was the immediate cause of the accident. However, a series of other factors contributed to the accident, which are also discussed. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Traffic accident reconstruction; Fatigue; Wear; Fracture

1. Introduction

One of the activities most affected by the great increase in industrial output and commerce after the creation of the South American Common Market (MERCOSUR) has been transportation. Truck and bus companies grew very quickly in a short period of time. However, roads and related infrastructure are improving at a rate that has not yet matched the needs. A considerable number of new trucks are being introduced, but small local companies still operate a great number of old trucks. Most of this heavy traffic runs on old, narrow (typically 6.80 m wide) two lane roads.

A characteristic of the Argentine truck business is that only very new trucks are of the “18 wheeler” type, in use in Europe and North America. Traditional tractor and trailer systems have been and still are in use, especially for transportation of agricultural products. The tractor (or chassis) includes the engine, cabin and a small cargo box, while the trailer has a front steering axle and one or two back axles, and is towed through an A-frame as indicated in Fig. 1. The A-frame (A), the two safety chains (B), the brake hoses (C), and the rotating platform (D) of the front (steering) axle of the trailer are seen in the figure. Although not shown in this figure, in parallel to the safety chains there is usually a helical spring to prevent the A-frame from dropping when not engaged to the tractor. This A-frame is connected to a mooring hoop in the tractor, by an eyebolt bolted to the A-frame, which is shown in Fig. 2. Control over the trailer can be difficult for the driver, especially when, as is usually the case, the weight of the trailer is much greater than the weight of the tractor.

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The engineering forensic analysis presented in this paper was carried out as a consequence of a front crash between a truck and a bus, with 15 deaths amongst the bus passengers. Having found a failure of a piece in the towing system of the truck, it was necessary to evaluate if this failure was the direct cause of the accident, and if so why this failure was produced, and who was responsible.

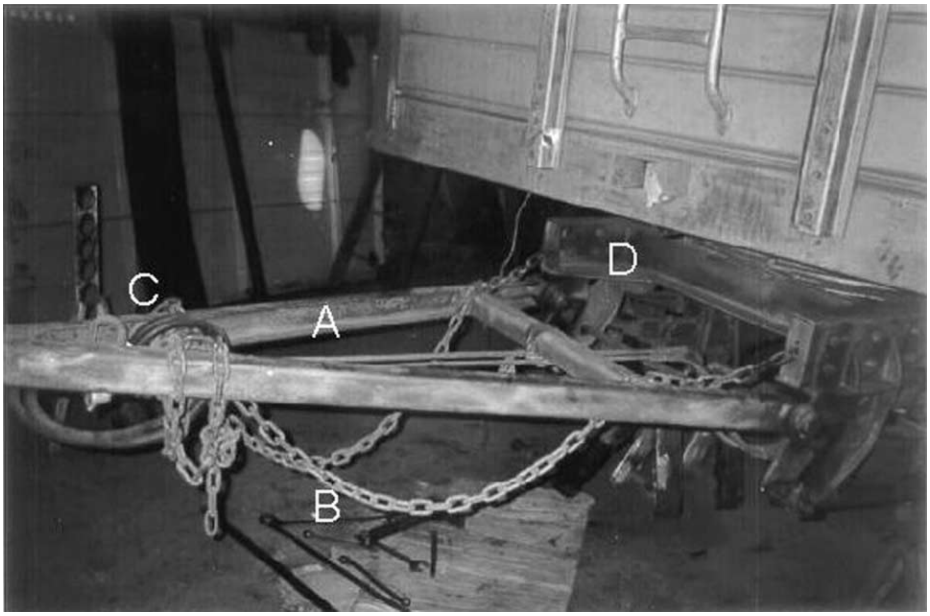


Fig. 1. Front view of trailer: A-frame (A), safety chains (B), brake hoses (C), and rotating platform (D) of the front (steering) axle.

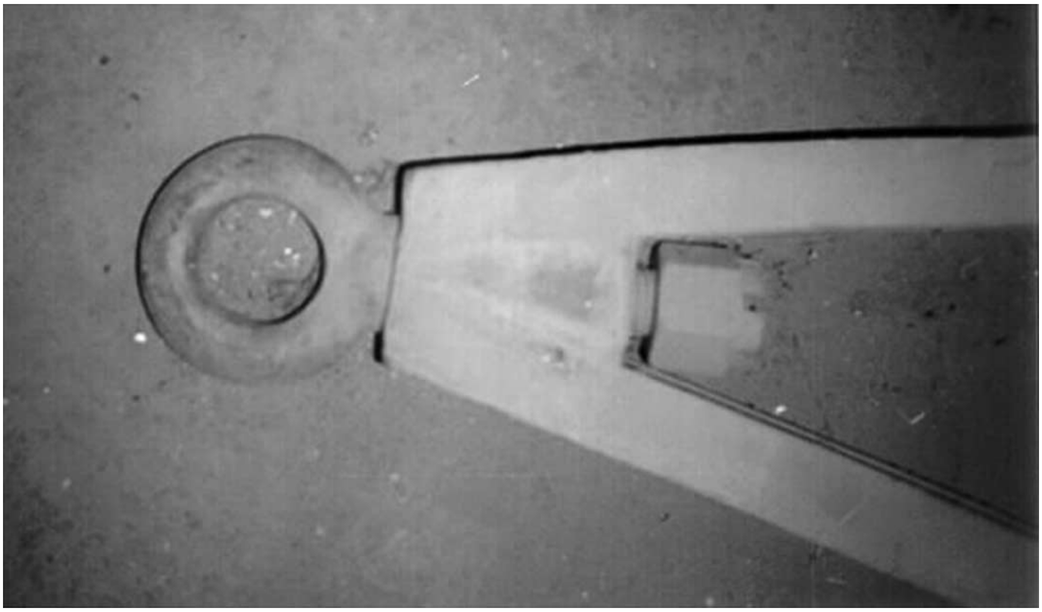


Fig. 2. Eye and bolt assembled to the trailer A-frame. The eyebolt is connected to the tractor mooring hoop.

2. Background, visual inspection and crash model

The crash discussed in this work occurred in daylight, in a straight length of a 6.8 m wide, two-lane road. The crash occurred on the bus lane, some 300 m downroad of a bridge, which at the time of the analysis had been recently repaired. People from the place stated that at the time of the accident there was a large pothole at the exit of the bridge [1]. An overview of the two-lane road at the crash site is seen in Fig. 3. The marks shown indicate the place where the bus and trailer impacted. Fig. 4 shows a sketch of the area of the accident. The scale is indicated in meters. The truck and the bus involved in the accident are identified.

Fig. 3. Overview of the two-lane road at the crash site The marks in the pavement indicate the place where bus and trailer impacted.

Three positions of the truck are defined as a, b and c, from the crossing of the bridge by the truck (a) up to the crash (c).

Several marks on the pavement revealed interesting aspects of the accident. These marks correspond to the A-frame of the trailer and to diverse parts of the chassis of both vehicles during the collision. Two areas are observed: 1–5 mm deep semicircular scratches, of 1–2 m radii, that begin in the truck's lane, and cross the central line of the route. These marks, shown in Fig. 5, are due to the scraping of the A-frame on the pavement. Large compressive deformations in the A-frame and bright scratches in the A-frame tip confirm this evaluation. The semicircular marks shown in Fig. 5 end up with other 5–20 mm deep marks, parallel to the route, located on the opposite lane. The A-frame fastener with a broken part of the bolt was found in

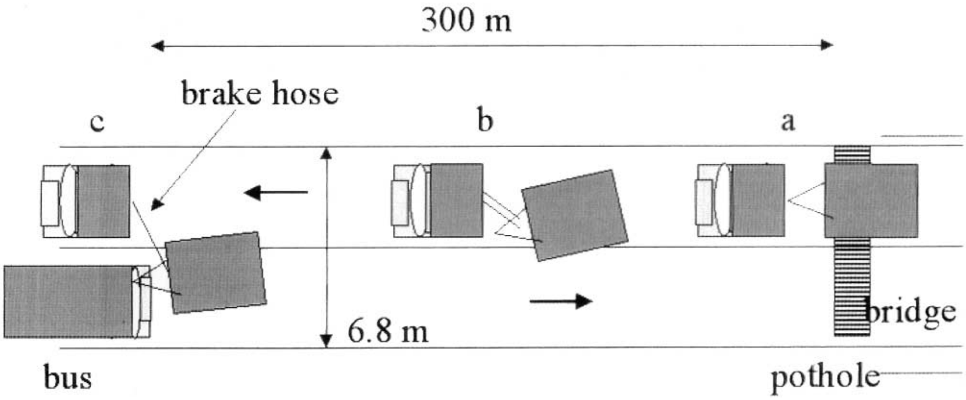


Fig. 4. Sketch of the area of the accident. (a) eyebolt breaks after crossing the bridge, (b) safety chains break, (c) bus and trailer crash.

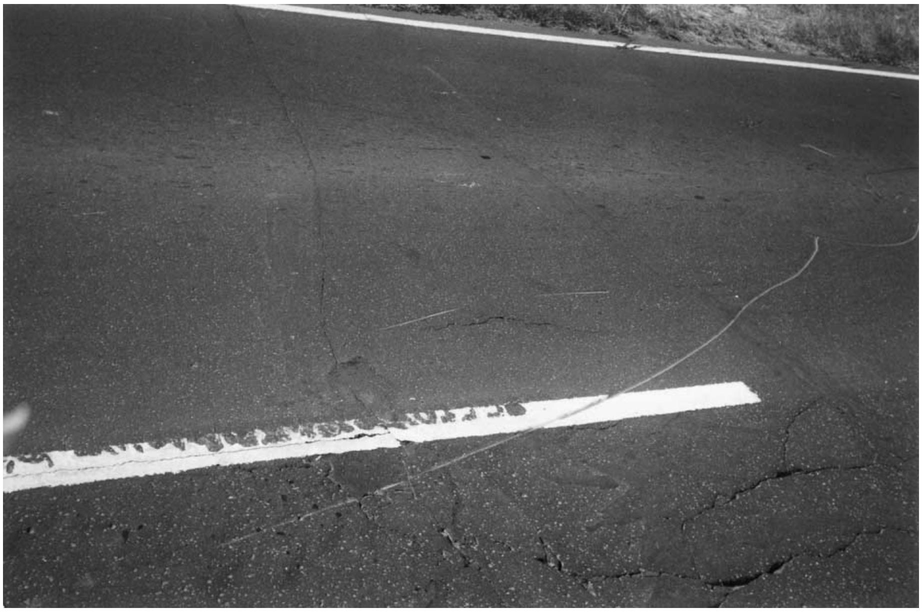
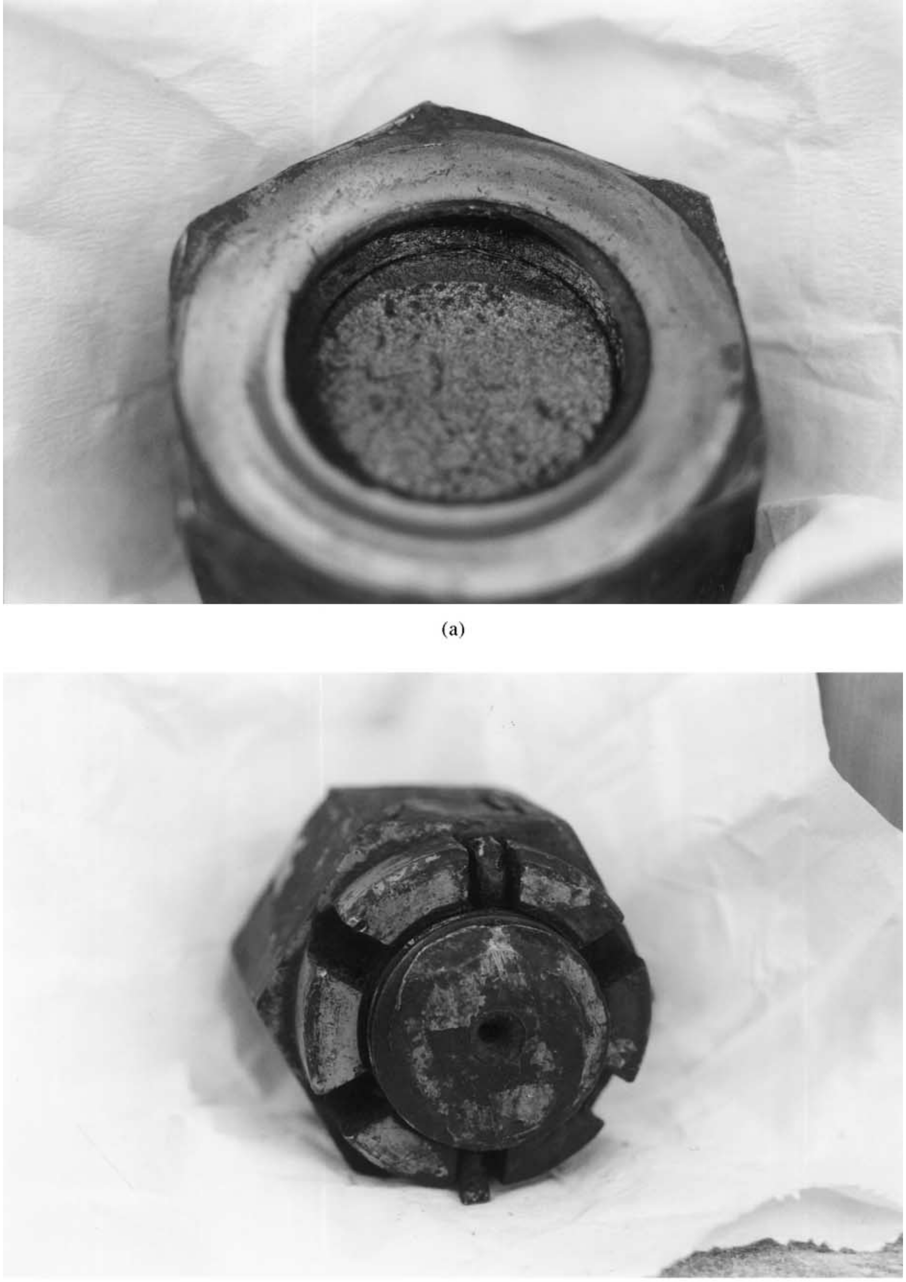


Fig. 5. Semicircular scratches on the pavement produced by the A-frame across the central line of the route.

the bank 10 m downroad from the bridge (see Fig. 6), while its washer was found about 50 m from the bridge. A link of the safety chain was found near the place of the crash, on the opposite bank. The retention spring was found broken, still attached to the trailer. A good correspondence between the marks in the pavement and the positions of the remains on the banks was obtained [2].


(a)

(b)

Fig. 6. The A-frame fastener with a broken part of the bolt, found in the bank 10 m downroad from the bridge.

Field obeservations allow one to conclude that the fracture of the bolt linking the tractor and the trailer took place when the trailer passed over a pothole in the route, at the exit of the bridge (position "a", Fig. 4). The tractor kept pulling the trailer through the safety chains (Fig. 1), for about 200 m, until the chains also broke (position "b"). After the fracture of the safey chains, the trailer entered the opposite lane, and was impacted by an oncoming bus (position "c"). Bad fortune was important in this accident. If the crossing between the truck and bus had happened 200 m later, the bus driver would have had time to see the trailer in his own lane and carry out some evasive maneuver. In this case, a possible human error can not be attributable to the drivers of the vehicles at the moment of the accident, but more probably to those responsible for the construction and maintenance of the truck and the road.

The length of the coupling hoses of the trailer's air brakes were long enough that the trailer could unhook and move laterally after the truck left the bridge and the bolt broke, without the hoses being uncoupled. This excessive length of the hoses is due to the neccessity of standardizing the tows, and of providing looseness during the tow maneuvers. In this case the trailer was not very far from the tractor at the moment of the impact with the bus, so the fact that the controls had not been activated before the tragedy does not necessarily imply that the breaking safety system had failed.

Bright marks appear on the lower edge of the left bar of the A-frame bar shown in Fig. 1. These marks were produced by contact with the safety chains of the trailer. This indicates that the safety chains were located in a crossed position. This disposition presents both advantages and disadantages over the normal parallel disposition of the chains. As possible advantages, they are necessary to retain the A-frame in the event of a fracture of the hook and retention spring, because when the chains are being tightened the A-frame remains horizontal. The crossing point of the chains works as a rotation point. In the common parallel disposition, the fracture of one of the chains produces a very small moment over the trailer toward the opposite side. In the crossed disposition the trailer rotates toward the side of the chain which fractures first. In our case, the left chain broke first, and then the trailer was dragged by the right chain for a short time, leaving the marks when being tightened. This generated a turn of the trailer toward the left, its entrance in the opposite lane and its impact with the bus.

3. Fractographic analyses

As concluded in the previous section, the crash occurred shortly after the fracture of the bolt linking the tractor and the trailer, that took place when the trailer passed over a pothole in the route. The truck was only 1 year old, so that the failure of the haulage system was unexpected. Therefore, all features of the damage process were studied in detail. Several flaws were detected in the assembly of the front train of the trailer. Deformation was found in the holes of the anchorage bolts of the rotating plate (see Fig. 7), not attributable to deliberate operations. Some cracking indicates an exhaustion of ductility due to plastic deformation. These deformations probably took place during the service life of the trailer, as a consequence of difficulties in the free turning of the plate.

Materials used in structures operating under conditions of variable loads in atmospheric media are exposed in service to a series of mechanisms of damage that can finally cause a failure: fatigue, corrosion, and static overloads or impacts [3]. These mechanisms produce accumulation of damage and propagate previous defects introduced during fabrication or in service. When these defects reach a critical size fracture takes place [4]. A failure analysis was carried out, with these objectives: (a) the identification of the cracking mechanisms that led to premature failure, and (b) the determination of the causes that created the conditions so that this mechanism occurred and generated the accident.

The broken connection piece is shown in Fig. 8. It is composed of an eyebolt that inserts in a cylindrical lodging inside the A-frame, to which it is fixed by means of a nut or fastener (see Fig. 6). The traction loads are supported by the nut. The eye itself is a cast steel piece that does not usually receive thermal treatment, which is welded to the bolt. Microstructural analyses of the bolt showed a mostly pearlitic structure, with ferrite as second phase, as shown in Fig. 9. A slight tendency to the formation of low toughness microstructures is observed. Widmastatten pearlite–ferrite ratio is around 85/15. Longitudinal banding of the grain boundary ferrite due to radial deformation during forging is observed. The thread was formed rather than machined, since lines of deformation are not discontinued by the threads [5]. Chemical characterization identified this steel as SAE 1048. Mechanical and fracture mechanics testing of the material lead to the

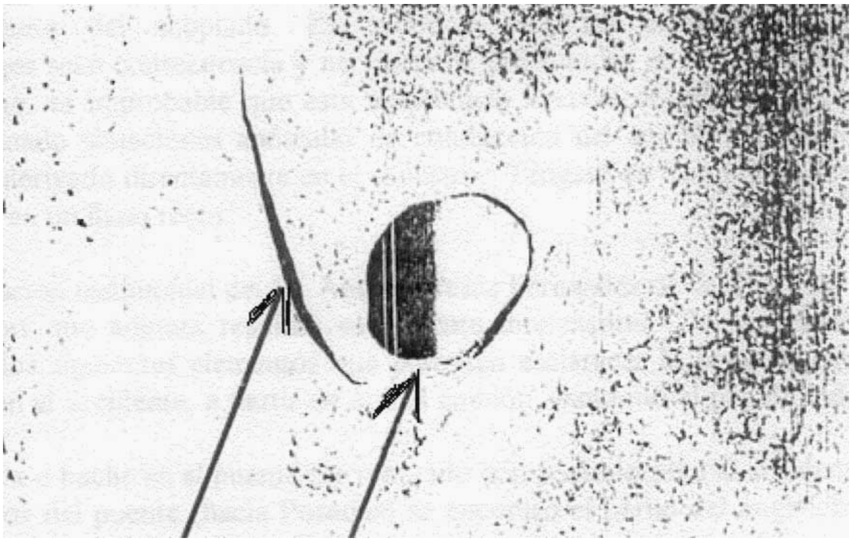


Fig. 7. Deformation and crack around one the bolt holes of the front axle rotating plate.

Fig. 8. Detail of the broken eye and bolt assembly.

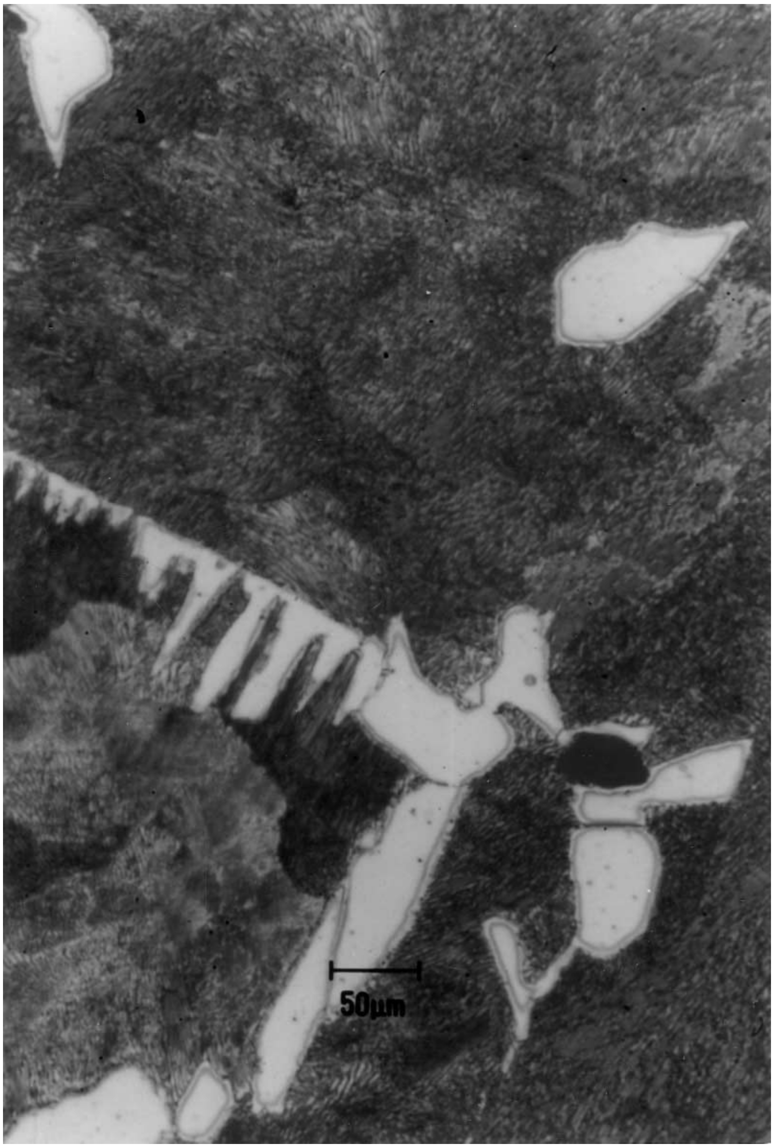


Fig. 9. (×200) Microstructure of the wrought SAE 1045 bolt material. Widmastatten pearlite–ferrite ratio is 85/15.

following properties: yield strength 420 MPa, ultimate tensile strength 680 MPa, fracture toughness 60 MPa $m^{1/2}$ [6]. The eye is a wrought SAE 1045 material.

Metallographic observations revealed that the bolt and eye assembly seen in Fig. 9 was welded with an austenitic (stainless steel) electrode, of type AWS 309. Austenitic fillers are used to weld materials of high strength and low toughness, like SAE 1045. Hydrogen cracking problems, common in these types of hardenable steels, are in this way minimized. On the other hand, austenitic weld metal presents low resistance to wear [7]. Fig. 10 shows high premature wear in the welded area. The bright surfaces in the sides of the bolt indicate that it rubbed against the walls of its lodging in the A-frame. From these marks, it

Fig. 10. Evidence of high premature wear in the eye to bolt weld, due to friction against the walls of its lodging in the A-frame.

was estimated that a gap of 8 mm existed due to incorrect adjustment of the nut of the fastener (exemplified in Fig. 2).

Figs. 6 and 11 show the two fracture surfaces of the bolt within the first thread inside the fastener. The fracture is clearly defined as initiating from a defect at the inside of the thread. The fracture bears a certain degree of plastic deformation, indicated by the torn ligament in a sector of about 90° (lower part of Fig. 11). This torn sector corresponds to the final sparation of the two parts of the fractured bolt. The surface of the fast fracture is of mixed type, with sectors of fibrous appearance (fracture by ductile microvoid coalescence) and sectors of crystalline appearance (fracture by cleavage). These characteristics are typical of a fracture above the ductile–brittle transition temperature of the material [8]. The Chevron marks show that the propagation of the fracture took place from top to bottom in Figs. 6 and 11, that is, it began in an initial crack and finished with the total separation of the material by plastic collapse. The final ligament is clearly identified because in its final stage the fracture followed two different surfaces, corresponding to two consecutive threads.

Fig. 12 shows that initiation of the fast fracture takes place from a crescent shaped crack, about 3–3.5 mm deep around 120° of the perimeter of the bolt. The shape of the crack and its smooth surface in this region are typical of low cycle fatigue crack growth due to tensile loads [4,5,8]. Inititation of the crack is not associated with a single defect, such as a corrosion pit, an inclusion, etc., but rather to the stress and strain concentration due to the geometry of the thread. Therefore, it is concluded that the fatigue crack was not related to material or fabrication defects, but rather to high cyclic loads during service.

4. Fracture mechanics assessment

Analytical and numerical models of load and stress distribution were used, considering the conditions of load and restraint. Finite element models of the bolt assumed a linear elastic behavior of the material [9]. The longitudinal maximum load that the bolt can resist before failure was assessed. This element transmits the total load between truck and trailer. Failure of a threaded steel component can occur as plastic collapse or fast fracture, typically starting in the bottom of the first and second thread, where the load transfer between fastener and bolt and the geometric stress concentration generate a highly stressed region, usually referred to as a hot spot [10]. Although local plastic deformation does not imply immediate fracture, it

Fig. 11. Fracture surface in the bolt. Note initiating crack within the first thread inside the fastener, and ligament torn by final plastic collapse.

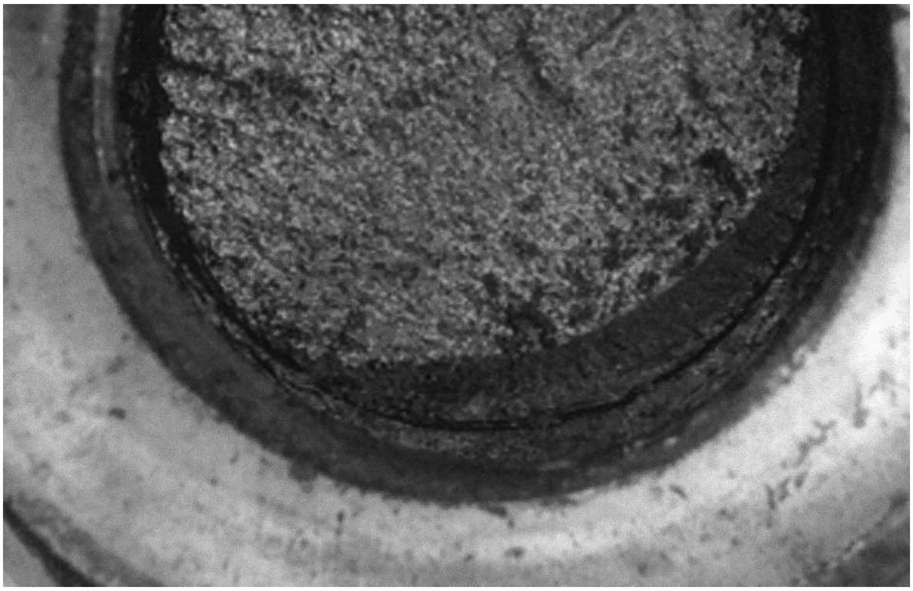


Fig. 12. Detail of fracture initiation from a cresent shaped 3.3 mm deep fatigue crack.

begins to generate damage due to the exhaustion of ductility of the material in the area. Under cyclic loads, a crack is eventually generated and begins to grow with time and load cycles. This mechanism originated the crack that grew in service and led to the final fracture of the bolt.

Typical results of finite element models indicate that in the bottom of the thread the Stress Concentration Factor is around SCF = 3.6 [11]. It was calculated that the hook in its original condition (without crack) could support a maximum longitudinal load of 10 ton without yielding. The real net load to which the bolt is subjected in service depends upon the following parameters: weight of the trailer, maximum accelerations or decelerations of truck and trailer, gaps in the haulage systems that can cause dynamic load amplification, and the speed of the loaded vehicle. The dynamic effect of the gaps acts as a multiplicative factor on the accelerations. A typical value of this dynamic factor is $A_d = 2$, that corresponds to the relationship between the loads generated on an elastic element by a weight under ideal static conditions and the loads generated by its fall from a zero height. The speed is directly related to the loads generated by the road surface.

When the truck begins to brake, the acceleration changes sense. This also happens when the trailer crosses an obstacle in the road (pothole, gutter, etc.). At some time the trailer pushes the truck. In that change of sense the dynamic amplification factor is $A_d = 2$. The total gap in the haulage system is the sum of the radial gap between eye and hook, longitudinal gap of the bolt within the A-frame, and radial gaps between holes and bolts in the rotating plate of the front axis. The gaps in the plate bolts are about 2 mm. The ovalization of the hole of the eye due to wear is 2.5 mm, to which the normal gap to allow turning and slipping should be added, giving a total gap of about 4 mm. The "throat" by wear in the area of the weld is 12 mm long. Discounting the thickness of the plate that produced that wear, this results in a 7–8 mm relative displacement between bolt and plate. The sum of these gaps gives a total longitudinal displacement of about 16 mm. The hook system in the tractor has an elastic crossbow element. Approximately 95% of the energy of dynamic deformation is absorbed by the elastic crossbow and the pin in the hook of the truck, and only 5% is absorbed by the hook bolt of the trailer. This simplified analysis gives a resulting dynamic amplification $A_d = 4.6$.

In the case of emergency braking with the trailer fully loaded, the maximum deceleration is approximately 8 m/s^2 [2]. For a maximum weight of the trailer of 28 ton and a dynamic factor of 2, the maximum longitudinal force is 45 ton. But this load is compressive. In this case the load is not transferred by the bolt but by the body of the A-frame (see Fig. 2). According to the engine power, maximum acceleration to the fully loaded trailer is about 2 m/s^2. Under dynamic conditions, this generates a traction force on the bolt of the hook of about 11 ton. Fatigue crack initiation is seldom observed when the maximum longitudinal stress is less than 50% the yield strength of the material. Considering an SCF = 3.6, it can be concluded that the maximum acceptable traction loads on the hook to avoid fatigue crack propagation from the first and second threads of the fastener is slightly lower than the operation loads. The estimates, although simple and prone to errors, were confirmed: the cyclic loads during service generated fatigue damage. A fatigue crack grew in a stable form during some time, until it reached a critical size that led to the complete fracture of the bolt.

There are three main factors that control the susceptibility of a component to fracture: (i) fracture toughness of the material, (ii) stress level, (iii) defect characteristics. Linear elastic fracture mechanics (LEFM) uses the concept of the stresss intensity factor, K. Fast fracture occurs when the applied K reaches a critical value, K_{Ic}. K_{Ic} represents the fracture toughness of the material. The applied K is given by [13]: $K = Y\sigma\sqrt{\pi a}$, where σ is the applied stress, a is the crack depth and Y is a factor that depends on the geometry. The equations presented by Newman and Raju [14] establish the value of K in each point in the tip of a semielliptic crack, for given values of applied nominal tensile and bending stressses.

Fast fracture and plastic collapse are simultaneously assessed by the failure assessment diagram (FAD) [12,15]. In a FAD, the ordinate axis, *Kr*, represents the relationship between the applied K and the fracture toughness of the material, while the abscissa *Sr* represents the relationship between the applied stress and the yield stress of the material. The external points to the curve in the FAD indicate failure situations, while the interior points represent situations of safety. The assessment points are defined when the fatigue cracked bolt is subjected to different loads. The failure conditions in the buttonhole bolt are reached when $Kr=0.35$, and $Sr=1.2$. This means that the failure occurred due to plastic collapse of the remaining ligament of the bolt, and not by brittle propagation of the fatigue crack.

When the material of the bolt enters the plastic regime, the applied real stress is calculated considering a small global stresss raise. A reasonable approximate value is SCF $=1.5$. The maximum load that would have caused the instantaneous collapse of the eyebolt in a condition free of previous defects is simply the product of its ultimate stress, the resistant area and this low SCF. A fracture load of 38 tons is obtained, that is, almost four times the load that starts the fatigue process. The presence of the fatigue crack reduces the load at fracture to about 25–30 ton. This value is still very high, so it should be concluded that the dynamic loads generated on the hook when the trailer passed over a step or pothole were very high in comparison with other similar events during the service life of the truck.

5. Fatigue assessment of the failed part

The excessive gaps observed during the visual inspection were caused by the inadequate adjustment of the fastener, wear of the haulage eyebolt due to metal contact and impact, and enlargement (deliberate or due to wear) of the holes of the bolts in the plate of the front train. The forces dynamically enlarged due to the gap in the haulage system generated two mechanisms of degradation during the year of use of the tandem truck–trailer, previous to the accident: plastic deformations in the elements that gradually accentuated the dynamic load amplification, and propagation of a fatigue crack in the thread, that gradually diminished the strength of the bolt until reaching a final value of 70% of its initial strength.

Paris and Erdogan demonstrated that crack growth by fatigue can be related with the stress intensity factor range through the relationship $\frac{da}{dn}=C\Delta K^m$, where C and m are material constants, $\Delta K=K_{\max}-K_{\min}$, maximum and minimum values of K during the fatigue cycle. Below a certain threshold ΔK_o, the cracks remain inactive. Bibliography data for the material SAE 1048 are: $m=3$, $C=1.5\times10^{-11}$, with da/dn in m/cycle and ΔK in MPa $m^{1/2}$ [5,11]. The number of cycles necessary to grow a crack at the bottom of the thread, from an initial depth of 0.5 mm until a final depth of 3.5 mm was calculated integrating numerically the Paris equation. An initial defect size of 0.5 mm was chosen, as it corresponds to the sensitivity limit of standard nondestructive test methods.

The unknown spectrum of loads during the service life of the truck was replaced by a constant amplitude equivalent load. Larger load cycles cause faster crack growth, and are usually only a few percent of the total (start and stop of the convoy, large potholes, etc.). A reasonable approach is to neglect the effect of the numerous small amplitude load cycles. The frequency of maximum load cycles was estimated between 10 and 50 per day. Considering a cyclic load of 11 ton and a SCF between 3 and 1.5, estimated fatigue lives are between 1000 cycles and 10,000 cycles, which yields extreme fatigue life estimates of 20 and 1000 days. This result fairly coincides with the age of the truck, approximately 200 days of use, which allows one to discard the assumption that some used parts could have been used in the haulage system.

6. Discussion

The previous analyses allows one to conclude that the crash was due to the failure of the eyebolt coupling the tractor hook with the trailer A-frame, after 1 year of use. The instant loads generated when the trailer passed over the pothole were large enough to propagate a ductile fracture from the pre-existing fatigue crack in the eyebolt. Previous events (potholes, accelerations, braking, etc.), however, were responsible for the fatigue propagation of the crack during service. The large loads applied to the trailer elements (eyebolt and rotating plate) caused cumulative plastic deformations that in turn further increased the size of the gaps and the dynamic load amplification, in a synergistic process of degradation that eventually included fatigue growth of a crack and ended up with the fracture of the bolt.

The bolt was subjected to a quick process of degradation due to wear and cyclic loads, increased by excessive gaps in the haulage system. These gaps must be related to construction and maintenance defects. In particular, two conditions can be identified as originating these defects. One is the excessive gap in the eyebolt, which must be related to a wrong assembly. No evidence of plastic deformation or wear were found in the bolt assembly, which could justify the in service occurrence of such gaps. The excessive gaps in the eyebolt orifice and in the rotating plate bolts are related to in service wear. In the last case, this wear is directly related to poor lubrication, while in the former case wear is possibly related to low material hardness and the large in service impact loads.

The mechanical factors that led to the failure have been related to in service damage of several components. Adequate maintenance and in service inspection could have avoided the occurrence of the final fracture of the bolt. A comprehensive verification system for truck and bus safety was introduced in the early 90s, including control of allowable weight and mechanical soundness. However, both frequency and methods of mandatory inspection are not adequate to detect wear or fatigue damage in the haulage system of cargo trailers. New, more stringent inspection guidelines should be implemented, which must include visual and magnetic particle inspection of welded and bolted parts of which failure could lead to serious accidents, as occurred in this case.

Failure probabilities could be reduced by increasing the diameter of the eyebolt. Figs. 2 and 8 show that a 30% increase in bolt diameter could be accommodated by introducing small changes in its lodging in the A-frame. Other factors that contributed to the accident are related to the inadequacy of the road conditions. This type of two-lane 6.80 m wide road has proved to be too narrow for present heavy traffic. Front crashes are common. In this case, the existence of the pothole at the exit of the bridge was directly related to the occurrence of the crash at that moment, but the failure was already imminent. The poor condition of the pavement in this and other roads frequently used by this truck were probably key factors in dramatically reducing the fatigue life of the eyebolt.

7. Conclusions

The engineering forensic analysis presented was carried out as a consequence of a front crash which occurred between a truck and a bus, with 15 deaths amongst the bus passengers. The crash and initial positions of the vehicles were determined by the study of the marks in the pavement, position and shape of indentations and other damage to the vehicles, and their final positions after the crash. Fractographic, metallographic and mechanical studies and numerical models of load transfer and crack propagation were made.

The failure analysis and materials characterization allowed one to conclude that the crash was due to the failure of the eyebolt coupling the tractor hook with the trailer A-frame, after 1 year of use. The bolt was subjected to a quick process of degradation due to wear and cyclic loads, increased by excessive gaps in the haulage system. A mechanical failure due to fatigue crack propagation, related to construction and maintenance defects, was the immediate cause of the accident. Present mandatory inspection methods are not adequate to detect wear or fatigue damage in the haulage system of cargo trailers. Other factors that contributed to the accident are related to the inadequacy of the road conditions.

Acknowledgements

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