FATIGUE DAMAGE AND A TRAFFIC ACCIDENT

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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 propagtaion was the immediate cause of the accident. However, a series of other factors contributed to the accident, which are also discussed.

Se presenta el análisis pericial de un accidente de tráfico que involucra un camión y un autobús. Se presentan estudios fractograficos, metalográficos y mecánicos, y modelos numéricos de transferencia de carga y propagación de fisuras. Una falla mecánica debida a fisuración por fatiga fue la causa inmediata del accidente. Sin embargo, otros factores contribuyeron al accidente, que son también discutidos.

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 meter wide) two lane roads.

A characteristic of 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 axe and one or two back axes, and is pushed through a lance as indicated in **Figure 1.** The lance (A), the two safety chains (B), the brake hoses (C), and the rotatitng platform (D) of the front (steering) axe of the trailer are seen in the figure. Although not shown in this figure, in parallel to the safety chains there is usually a hellicoidal spring to sustain the lance from dropping when not engaged to the tractor. This lance is connected to a mooring hoop in the tractor, by a buttonhole bolted to the lance, which is shown in **Figure 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.

The engineering forensic analysis presented in this paper was carried out as a consequence of a front crash occurred between a truck and a bus, with 15 deaths amongst 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 in such case why this failure was produced, and who was responsible.

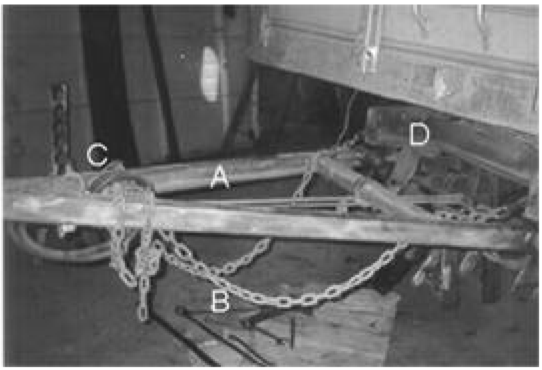

Figure 1. *Front view of ftrailer: lance (A), safety chains (B), brake hoses (C), and rotatitng platform (D) of the front (steering) axe*

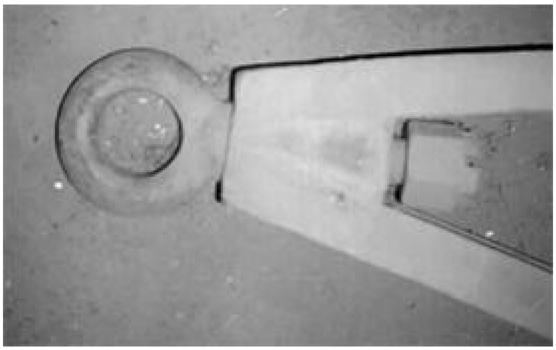

Figure 2. *Buttonhole and bolt assembled to the trailer lance. The buttonhole is connected to the tractor mooring hoop.*

2.- BACKGROUND, VISUAL INSPECTION AND CRASH MODEL

The crash discussed in this work occured in daylight, in a straight tract of a 6.8 m wide, two lane road. The crash occured on the bus lane, some 300 meters downroad 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 **Figure 3.** The marcks shown indicate the place where bus and trailer impacted. **Figure 4** shows a sketch of the area of the accident. Scale is indicated in meters. The truck and the bus involved in the accident are identified. 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).

Figure 3. *Overview of the two lane road at the crash site The marcks in the pavement indicate the place where bus and trailer impacted.*

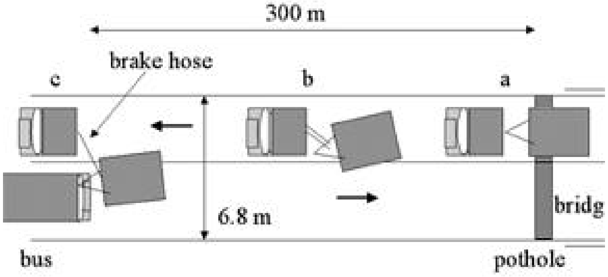

Figure 4 *Sketch of the area of the accident. (a) buttonhole bolt breaks after crossing the bridge, (b) safety chains break, (c) bus and trailer crash.*

Several marks on the pavement revealed interesting aspects of the accident. These marks correspond fundamentally to the lance of the trailer and to diverse parts of the chassis of both vehicles during the collision. Two areas are observed: 1 to 5 mm deep semicircular scratches, of 1 to 2 metre radii, that begin in the truck´s circulation lane, and cross the central line of the route. These marcks, shown in **Figure 5**, are due to the haulage of the lance onto the pavement. The lance shows indications of having been deformed by compression, see **Figure 6.** Bright scratches found in the lance tip also confirm this evaluation. The semicircular marks shown in figure 5 end up with other 5 to 20 mm deep marks, parallel to the route, located on the opposite circulation lane. The lance fastener whith a broken part of the bolt was found in the bank ten meters downroad from the bridge, see **Figure 7,** while its washer was found about 50 meters 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 were obtained [2].

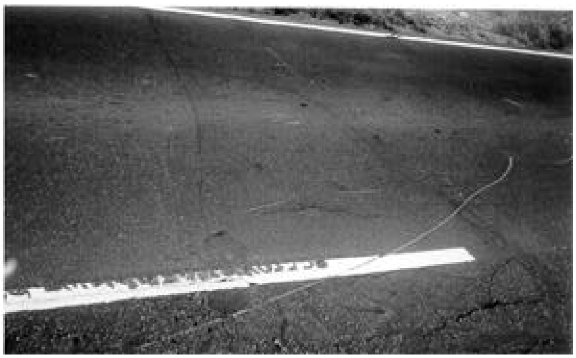

Figure 5. *Semicircular scratches on the pavement produced by the lance cross the central line of the route.*

Figure 6. *The lance was deformed by compression, bright scratches are found in its tip*

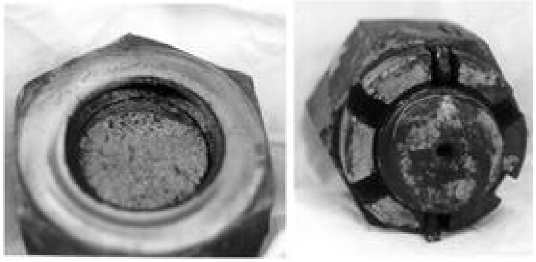

Figure 7. *The lance fastener whith a broken part of the bolt, found in the bank ten meters downroad from the bridge.*

Field obeservations allow to conclude that the fracture of the bolt linking the tractor and the trailer took place when the trailer stepped on a pothole in the route, at the exit of the bridge (position “a”, figure 4). The tractor kept pulling the trailer thorugh the safety chains (figure 1), for about 200 meters, until the chains also broke. (position “b”). After the fracture of the safey chains, the trailer invaded the opposite lane, and was impacted by an incoming bus (position “c”).. Bad fortune was important in this accident. If the crossing between truck and bus had happened 200 meters 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 so that the trailer could unhook and move laterally after the truck abandoned the bridge and the bolt broke, without the hoses being uncoupled. This excessive length of the hoses is due to the necessity 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 border of the left bar of the lance bar shown in figure 6. These marks were produced by contact with the safety chains of the trailer. This indicates that the safety chains were located in crossed position. This disposition presents advantages and inconveniences over the normal parallel disposition of the chains. As possible advantages, they are necessary to retain the lance in the event of a fracture of the hook and retention spring, because when the chains are being tightened the lance 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 right chain broke first, and then the trailer was dragged by the left 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 contrary lane and its impact with the bus.

3.- FRACTOGRAPHIC ANALYSES

As concluded in the previous section, the crash occured shortly after the fracture of the bolt linking the tractor and the trailer, that took place when the trailer stepped on a pothole in the route. The truck was only one 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 (figure 1), 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 turn 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 occured and generated the accident.

The broken fixation piece is shown in **Figure 8.** It is componsed by a buttonhole and a bolt that inserts in a cylindrical lodging inside the lance, to which is fixed by means of a nut or fastener (see figure 7). The traction loads are supported by the nut. The buttonhole 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 **Figure 9**. Scarce tendency to the formation of low toughness microstructures is observed. Widmastatten pearlite - ferrite ratio is around 85/15. Longitudinal banding of the ferrite in grain boundary due to radial deformation during forging is observed. The thread was laminated rather than mecanized, since lines of deformation are not discontinued by the threads [5]. Chemical characterization idnetified this steel as a SAE 1048. Mechanical and fracture mechanics testing of the material lead to this properties [6]: yield strength 420 Mpa, Ultimate Tensile Strength 680 MPa., Fracture toughness 60 MPa $m^{1/2}$. The buttonhole is a wrought SAE 1045 material.

Figure 8. *Detail of the broken buttonhole and bolt assembly.*

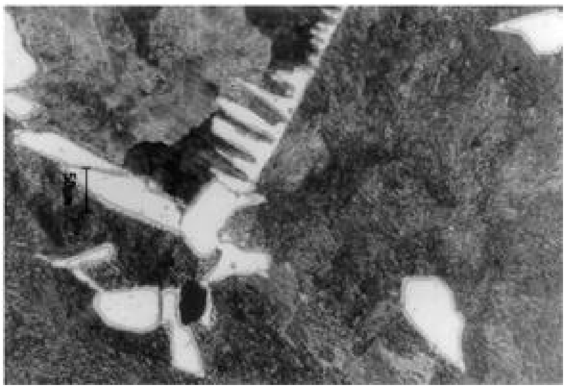

Figure 9. *(X200) Microstructure of the wrought SAE 1045 bolt material .Widmastatten pearlite - ferrite ratio is 85/15.*

Metallofraphic observations revealed that the bolt and buttonhole assembly seen in Figure 9 was welded with an austenitic (stainless steel) electrode, of the type AWS 309. Austenitic fillers are used to weld materials of high resistance and low toughness, like the SAE 1045. Hydrogen cracking problems, common in these types of hardenable steels, are in this way minimized. On the other hand, austenític weld metal presents low resistance to wear [7]. **Figure 10** shows high premature wear in the welded area. The bright surfaces in the sides of the bolt indicate that it slipped against the walls of its lodging in the lance. From these marcks, it was estimated that a gap of 8 mm existed due to incorrect adjustment of the nut of the fastener (exemplified in figure 2).

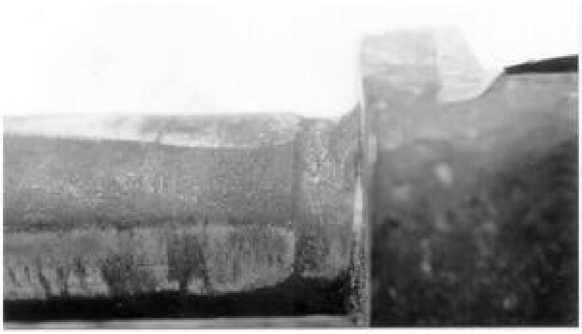

Figure 10. *Evidence of high premature wear in the buttonhead to bolt weld, due to friction against the walls of its lodging in the lance.*

Figures 7 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 figure 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 clieavage). These characteristics are typical of a fracture above the ductile – brittle transition temperature of the material [8]. The Chevron marcks show that the propagation of the fracture took place from top to bottom in figures 7 and 11, this is, it began in an initial crack and finished with the total separation of the material by plastic collapse This final ligament is clearly identified because in its final stage the fracture followed two different surfaces, corresponding to two consecutive threads.

Figure 12 shows that initiation of the fast fracture takes place from a half penny shaped crack, about 3 to 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 to 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, tipically 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 stressesed region, ususally referred to as hot spot [10]. Although local plastic deformation does not imply immediate fracture, it 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.

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

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 buttonhole and hook, longitudinal gap of the bolt within the lance, 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 buttonhole due to wear is 2.5 mm, to which the normal gap to allow turn and slip 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, results in a 7 to 8 mm relative displacemnt 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 $A_d = 4.6$.

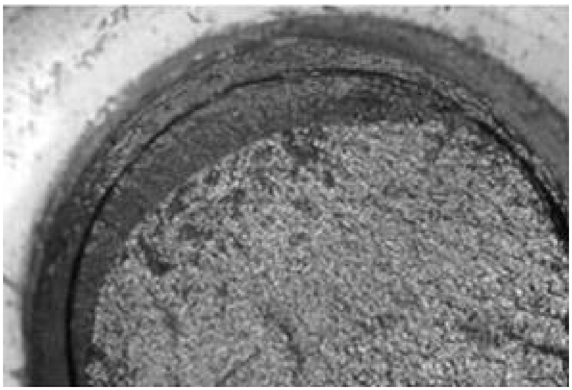

Figure 12. *Fracture initiation from a half penny shaped 3.3 mm deep fatigue crack.*

In the case of an emergency braking with the trailer fully loaded, the maximum deceleration is approximately 8 m/sec^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 lance (see figure 2). According to the engine power,. maximum acceleration to the fully loaded trailer is about 2 m/sec^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, (ii) defect characteristics, and (iii) fracture toughness of the material. 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, KIc. This way, KIc represents the fracture toughness of the material. 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 semielíptic crack, for given values of applied nominal tensile and bending stressses.

Fast fracture and plastic collpase 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 stresss 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 in plasticity, 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 buttonhole 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. When the material of the bolt enters in plasticity, the applied real stress should be. The presence of the fatigue crack reduces the load at fracture to about 25 to 30 ton.. This value is still very high, for what it should be concluded that the dynamic loads generated on the hook when the trailer passed on the step or pothole were very high in comparison with other similar events during the service life of the truck.

5.FATIGUE ASSESSMENT OF FAILED PART

The excessive gaps observed during the visual inspection were caused by the inadequate adjustment of the fastener, wear of the haulage buttonhole 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 $da/dN = C \ \Delta K^m$, where C and m are material constants, $\Delta K = Kmax \ -Kmin$, maximum and minimum values of K during the fatigue cycle. Below a certain value threshold ΔKo, the cracks remain inactive. Bibliography data for the material SAE 1048 are: m = 3, C = 1.5 10-11, with da/dn in meters/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 clalculated integrating numerically the Paris equation. An initial defect size of 0.5 mm was chosen, as it corresponds to the sensitivity limit of standard non destructive 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 1.000 cycles and 10.000 cycles, which yields extreme fatigue life estimates of 20 and 1.000 days. This result fairly coincides with the antiquity of the truck, approximately 200 days of use, which allows to discard the assumption that some used parts could have beien used in the haulage system.

6. DISCUSSION

The previous analyses allow to conclude that the crash was due to the failure of the buttonhole bolt coupling the tractor hook with the trailer lance, after one year of use. The instant loads generated when the trailer passed the pothole were large enough to propagate a fast fracture from the preexisting fatigue crack in the buttonhole bolt. 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 (buttonhole, bolt 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 buttonhole bolt, which must be related to a wrong assembly. No evidence of plastic deformations or wear were found in the bolt assembly, which could justify the in service occurance of such gaps. The excessive gaps in the buttonhole 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 lead 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 90's, including control of allowable weight and mechanical soundness. Howerver, 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 tjhose welded and bolted parts which failure could lead to serious accidents, as occurred in this case.

Other factors that contributed to the accident are related to the inadecuacy of the road conditions..This type of two – lane 6.80 metre wide road has proved to be too narrow for the present heavy traffic. Front crashes are common. In this case, the existence of the pothole at the esit of the bridge was directly related to the occurrence of the crash in 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 buttonhead bolt.

7. CONCLUS1ONS

An engineering forensic analysis presented was carried out as a consequence of a front crash occurred between a truck and a bus, with 15 deaths amongst 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 damages in 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 to conclude that the crash was due to the failure of the buttonhole bolt coupling the tractor hook with the trailer lance, after one 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 inadecuacy of the road conditions.

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REFERENCES

1. Otegui, J.L,: Binder C.A. s/ supuesto multiple Homicidio culposo en accidente de transito. Juzgado Instruccion No. 1, Corrientes, Argentina, 1994.
2. Baker, J.S., Fricke L.B. “The Traffic Accident Investigation Manual”. Northwestern University Traffic Institute, USA, 6th. Ed., 1986.
3. International Institute of Welding (IIW), document IIW SST-1141 - 89: Application of an Eng. Critical Ass. in Design, Fabr. and Inspection to assess the fitness for purpose of welded structures."
4. Anderson TL: Fracture Mecahnics, fundamentals and applications, 2nd. Ed., CRC Press, Miami, USA..
5. Fuchs, H.O., “Metal Fatigue in engineering”, 1980.
6. ASTM E399/87 : Standard procedures for the determination of Kic of metallic materials. American Society for Testing of Materials, 1987.
7. “AWS Welding Handbook – Volume 4, Part 2: Materials and Applications”. 8th ed., Amercian Welding Association, Miami, USA, 1998.
8. Elementary Engineering Fractrure Mechanics. D. Broek.1982
9. ALGOR Finite Element Design Software. Algor Inc., USA, 1998.
10. Haviland. G: “Designing with Threaded Fasteners”, Mechanical Engineering, 1983
11. Barsom J, Rolfe S: Fracture and Fatigue Control in Structures, Prentice Hall, 2nd. edition.
12. BSI PD6493/91 "Guidance on some methods for assessing the acceptability of flaws in fusion welded structures". British Standards Intitution, London, 1991.
13. Tada, H.; Paris, P.C. and Irwin, G.R.: The Stress Analysis of Cracks Handbook." DEL Research Corp., Hellertown, Pennsylvania (1973)
14. J. Newman, I. Raju: An empirical stress - intensity factor equation for the surface crack." Eng. Fracture Mechanics, Vol.15, No.1-2, 1981,pp.185-201.
15. Nuclear Electric: “R6 -CODE: Software for assessing the integrity of structures containing defects”. London, UK, 1993.