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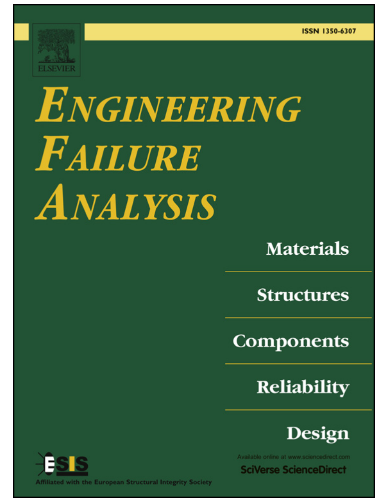


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**Abstract**

This paper reports a failure mode analysis of a boxer diesel engine crankshaft. Crankshafts are components which experiment severe and complex dynamic loadings due to rotating bending combined with torsion on main journals and alternating bending on crankpins. High level stresses appear on critical areas like web fillets, as well as the effect of centrifugal forces and vibrations. Since the fatigue fracture near the crankpin-web fillet regions is one of the primary failure mechanisms of automotive crankshafts, designers and researchers have done the best for improving its fatigue strength. The present failure has occurred at approximately 2,000 manufactured engines, and after about 95,000 km in service. The aim of this work is to investigate the damage root cause and understand the mechanism which led to the catastrophic failure. Recommendations for improving the engine design are also presented.

**Keywords**: failure mode analysis, automotive crankshaft failures, crankshaft failures, failure mechanisms.

## 1. Introduction

Engines have gone through significant changes since that the automobile was first introduced in the 1880s, one of the most important inventions of the nineteen century which had also a significant impact on our industry and society. Automobile industries are always interested to develop new products that meet the market requirements.

Crankshafts are power shafts of engines with a complex geometry having crankwebs and crankpins which are additional bearing surfaces whose axis is offset from that of crank. This component is placed into the crankcase (on the bedplate) and is supported by journal shell bearings. Each offset part of the crankshaft has a bearing surface known as crankpin to which the connecting rod is attached. It converts the linear (reciprocating) motion of pistons into a rotary motion that can be transmitted through a drive line system. The power from the burnt gases in the combustion chamber is delivered to the crankpin through the pistons and connecting rods.

A crankshaft is subjected to several forces that vary in magnitude and direction (multiaxial loading). Bending stress and shear stress due to twisting are also common stresses acting on crankshafts. Torsional loadings appear as result of the power transmission known as torque or binary.

The crankshaft is drilled with a network of oil passages to deliver lubricating oil under pressure to the oil galleries and bearings. In general, they have also counterweights in order to prevent undesirable vibrations and are added to offset the weight of the piston and connecting rod assemblies. At the rear of the crankshaft, a flywheel is assembled for damping the power pulses from the engine. The crankshaft main journals rotate in a set of supporting bearings (main bearings), causing the offset rod journals to rotate in a circular path (translation movement) around the main journal centres. The diameter of that path is the engine stroke when the piston moves up and down in its cylinder.

Many researchers have concluded that fatigue failures are largely due to cyclic bending loading combined with torsion at critical fillet regions. In order to avoid recurrence of failures, machining and final grinding has to be done carefully for preventing discontinuities or crack-like defects in the fillet region [1]. Other studies of broken power shafts by fatigue also show how important is this matter [2-8] when preventive design actions are not taken into account.

Fig. 1 (a) and (b) shows a typical crankshaft of a boxer diesel engine with the main and usual nomenclature. Crankshafts normally have either integral or attachable counterweights which are used to balance dynamic forces that occur during the engine operation. These counterweights compensate the centrifugal forces created by each crankpin linked to crank webs during the crankshaft rotation about the main journal axis. In the absence of the counterweights, the crankpin mass tend to bend and distort the crankshaft causing excessive edge loading in the main bearings. Therefore, each half crankweb is generally extended in the opposite direction to that of crankpin, to counterbalance the radial mass effects.

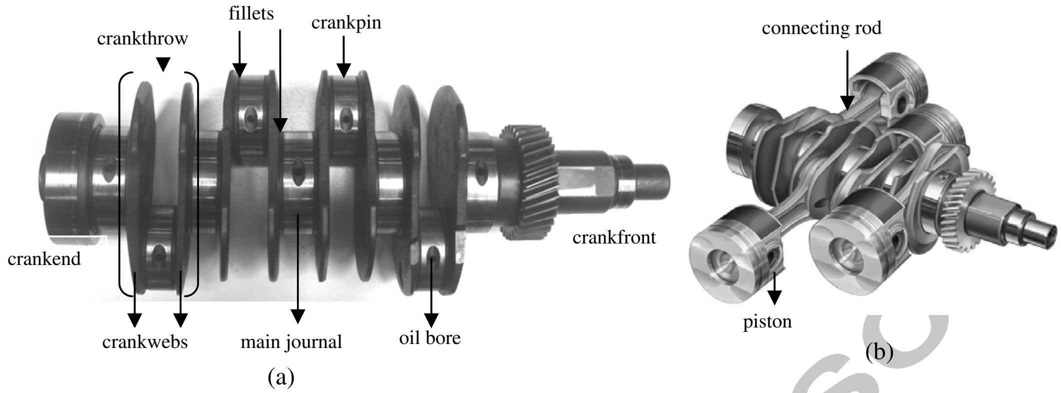


**Fig. 1.** (a) Typical crankshaft with the main and usual nomenclature, and (b) pistons at horizontal position.

Fatigue failures occur due to the application of fluctuating stresses that are much lower than the stress required to cause failure during a single application of stress. Fatigue failures generally start at critical points where metallurgical and structural defects exist and therefore high local stresses are favourable, such as zones of stress concentration present at sharp geometry, changing of the cross-sectional area, etc.

Being the fatigue process formed by an initiation zone and another one by propagation. The initiation is much localized and it has origin close to the crankpin-web or main journal fillets due to a high stress concentration frequently as result of a deficient fillet radius or wrong rectification of the crankpin and fillets. In addition, the crankshaft material is quite sensitive to local metallurgical defects [1].

Crankshafts are engine power shafts that run with harmonic torsion combined with cyclic bending stress due to radial loads of combustion chamber pressure [3]. Most of crankshafts that failed by fatigue are due to cyclic bending under opening mode I.

Bending causes tensile and compressive stresses at crankpin-web fillets and main journals. The torsion due to torque causes shear stress mainly on the main journals. Being the crankshafts one of the most highly stressed engine components, it is noted that the stress increases four times as the engine speed doubles. When a crack is eventually detected in a crankshaft it should be rejected, because is generally assumed that may sudden break if continues in service. Accurate stresses are critical input to fatigue analysis and optimization of crankshafts and the performance of any engine largely depend on its size and working in dynamic conditions [7]. The developing of robust fatigue design methods such the use of Finite Element Analysis (FEA) has significantly contributed to achieve this objective. Cracks in power shafts, such as crankshafts, generally start at surface of journals and growth under mixed-mode ($\Delta K_I + K_{III}$): cycle bending, mode I ($\Delta K_I$), combined with steady torsion, mode III ($K_{III}$). This statement comes from the cyclic bending stresses due to the misalignment between main journals or the effect of the force on crankpin transmitted by the connecting road at top centre (TDC). The steady torsion arises from the power transmitted by the shaft. Therefore crankshafts are generally subjected to rotating bending combined with steady torsion on main journals, and alternating bending at crankpins [9].

Automobile manufacturers are always in competition to develop a new motor that responds quickly in power and reduced consumption. The motor of this case study is an example of innovative design and successful in the automotive industry. The pistons move towards each other like boxer's gloves at the beginning of a match. It works in a horizontal position instead of the vertical line position, i e. cylinders and pistons are on a horizontal plane, see Fig. 1 (b). These engines offer a low gravity centre and thereby may run with better stability and control. This layout of cylinders is generally known as boxer engine which name was adopted because each pair of pistons moves simultaneously like boxers fighting. These engines can run very smoothly and free of unbalanced forces with a four-stroke cycle and do not require counterweights to balance the weight of the reciprocating parts, which are required for other engine configurations. Having a light mass, this crankshaft allows have a nervous motor with a better response in acceleration and power due to the low inertia.

Fig. 2 shows a boxer crankshaft assembled on the bedplate of the half block. The engine is light weighted and compact block. To take account this issue, a hybrid structure of aluminium and iron has been adopted. Cylinders and steel halves of main journal bearings are put into the foundry box to produce an aluminium alloy molten block.

Crankshafts are typically manufactured from forged steel, nodular cast iron and austempered ductile iron. They should be readily shaped, machined and heat-treated, with an adequate strength, toughness, hardness, and high fatigue strength. A challenge in induction surface hardening is to ensure a slight variation in hardness and the existence of compressive residual stresses with proper magnitude and distribution in transition areas to the hardness of the base material. Fillet rolling has also traditionally been used to induce compressive residual stresses at the crankshaft fillets, making the process of fillet rolling quite beneficial to fatigue strength reducing significantly premature failures. The fatigue strength of crankshafts is also increased by using a radius at the ends of each main and crankpin journals. The radius itself reduces the stresses in these critical areas and if these ones are rolled it creates a compressive residual stress on the surface which prevents cracks from forming.

**Fig. 2.** Boxer crankshaft placed on the bedplate and into the half block's motor.

All diesel crankshafts are heat treated. This heat treating is done to increase wear resistance by the effect of surface hardness leading to an improving of fatigue strength. A failure investigation of a nitride crankshaft revealed that the partial absence of the nitride layer in the fillet region decreased the fatigue strength and eventually in fatigue initiation and propagation in weaker region [10-12].

The aim of this work is to study the failure mechanism and root cause of a damage crankshaft of a boxer diesel motor. This type of failure is recurrent among 2 000 of produced engines. This case study holds the following steps: short crankshaft failure review which supports the failure analysis; identification of failure mechanism (how did it fail?); determination of root cause of failure (why did it fail?); discussion of results in order to support the hypothesis of the failure mode analysis which led to the root cause of failure conclusion; finally, some recommendations for preventing future failures will be also presented.

## 2. Material and procedures

### *2.1 Motor specifications*

The diesel engine that will be analysed due a fracture of crankshaft is a boxer motor. It has the following main specifications: displacement: 2000 cm$^3$; diameter cylinder: 100 mm; max power: 150 HP; max torque: 350 N·m. In Fig. 3 is shown the performance curves of this boxer motor: maximum torque at 1800 and 2400 rpm, and a maximum power of 112 kW at 3600 rpm.

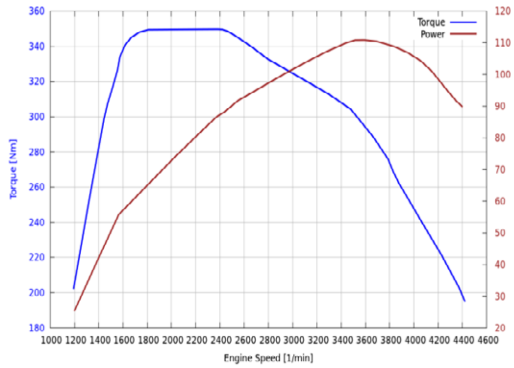


**Fig. 3.** Performance curves of boxer motor, torque [N.m] and power [kW]

*2.2 Investigation method*

First, the analysis was directed for the crankshaft failure. Since the fatigue bending was evident, the origin of the abnormal bending stresses was investigated. Two support steel shell halves were found broken under the shell bearings and cracks were also detected at the bedplate bridges. Then the correlation among those defects was deeply analysed in order to find the root cause of crankshaft failure.

*2.3 Crankshaft failure description*

The crankshaft was found broken at crankthrow No. 3. Verified all spares of motor, they were found in good use conditions without any abnormalities. All surface journals and shell bearings were free of any scratches or injured parts. Except the damage crankshaft and two main journal bearings, all parts of diesel engine were found as new ones. Fig. 4 shows the failed crankshaft at the crankweb nº 6. In Fig. 4 (c), close to crack initiation, are observed ratchet marks which are an indication of high stress concentration [2,4] at the crankpin-web fillets.

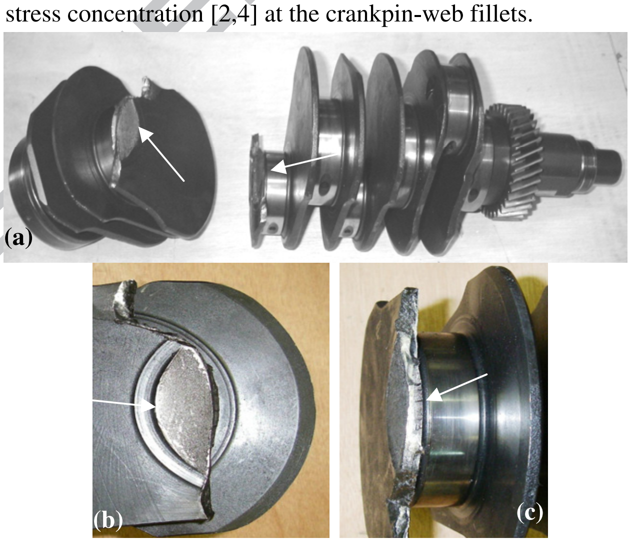


**Fig. 4.** (a) Failed crankshaft showing the morphology of the surface crack; (b) and (c) the crack initiation sites at crankweb No. 6.

This boxer motor type has frequently had a recurrent failure among 2,000 manufactured motors and after about 95,000 km of service. Failures have similar features: the crankshaft breaks itself at the crankpin No. 3 at the crankpin-web fillet. A more careful observation of the bedplate allowed finding two support steel shell haves where two half shell bearings are based. All support steel shell halves are brazed to the bedplate by a hybrid foundry for supporting the shell bearings. Two of those steel shells, in the bedplate middle, were found broken close to the bolts for tightening of two motor block halves. Furthermore, under both steel shell halves, the bridges of the bedplate in aluminium alloy appeared with transversal cracks, one crack in each bridge, and close to the side of the mentioned broken pieces, as is shown in Fig. 5.

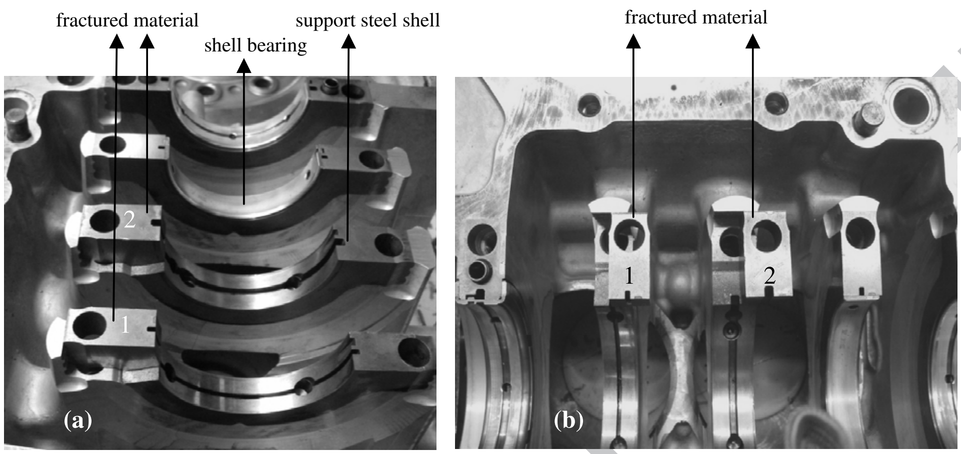


**Fig. 5.** (a) Fractured samples (No.1 and No. 2) and (b) the same samples in detailed view.

Fig. 6 shows in (a) the found cracks at two thrust steel shells (No.1 and No. 2) and in (b) the found cracks in the bedplate aluminum bridges. On the steel shells are also shown the shell bearings.

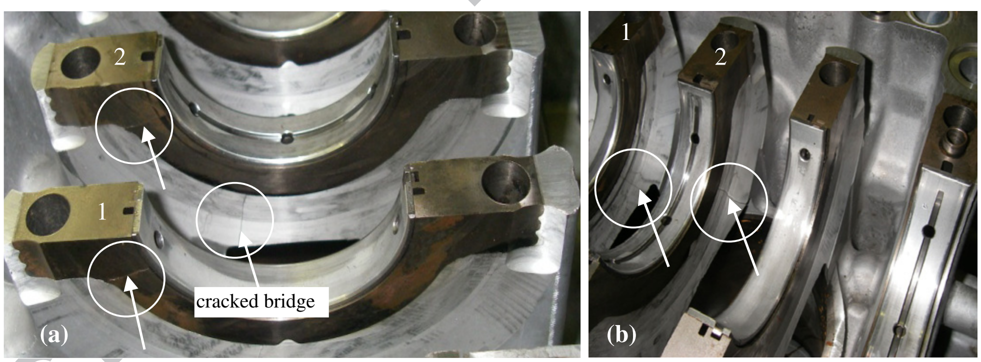


**Fig. 6.** (a) Steel shells based on the bedplate bridges the white arrows showing the found cracks; (b) the aluminium bridge cracks under the support steel shells.

## 3. Results and discussion

The first finding of damage is that the crankshaft failed on the crankpin-web No. 6, see Fig. 4 (a) and (b). Under the crankshaft, two central support steel shells were broken, as is shown in Fig. 5 and Fig. 6, from where two samples 1 and 2 were removed to analyse. These steel shells support the shell bearings on the bedplate aluminium bridges. Observing the surface crack morphology it is clear that the mechanism of failure was fatigue by bending, under mode I. Therefore if the crankshaft was under severe bending probability means that the bedplate yielded due to weakness.

The bedplate yielded as a consequence of the fatigue cracks found on the support steel shells and bedplate bridges, see Fig. 6. It seems clear that cracks have started at the sites pointed out by the white arrows on surface, from where samples No. 1 and nº 2 were collected, see Fig. 7 (a). Therefore the crankshaft fatigue process is after the cracking of the support steel shells and bedplate bridges. These steel shells were placed into the aluminium casting mold. Cracks have started there because the fillet radius of back side of steel shells was not adequate (close to the crack initiation, the fillet changes to a surface like a step) as is seen in Fig. 8 (a), (c) and (d) pointed by the white arrows. Therefore these broken pieces present zones that create the necessary conditions to initiate the cracks, and this can be the root cause of failure.

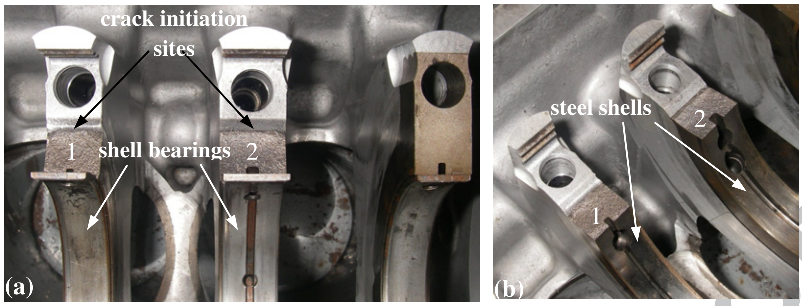


**Fig. 7.** (a) Places left by two fractured pieces with the screw bores of two block halves, and (b) the support steel shells.

Samples No. 1 and No. 2, Fig. 8 (b), were observed by SEM on the crack initiation sites. Fig. 9 shows the SEM micrographs at 200X and 500X magnification. Material defects and abnormal wear were not found. On the fatigue surface morphology were not observed any beach marks, but the crack initiation sites seem to be evident being a consequence of high stress concentration at the back side of the support steel shells, with a geometry that changes like a step, see Fig. 8 (c) and (d).

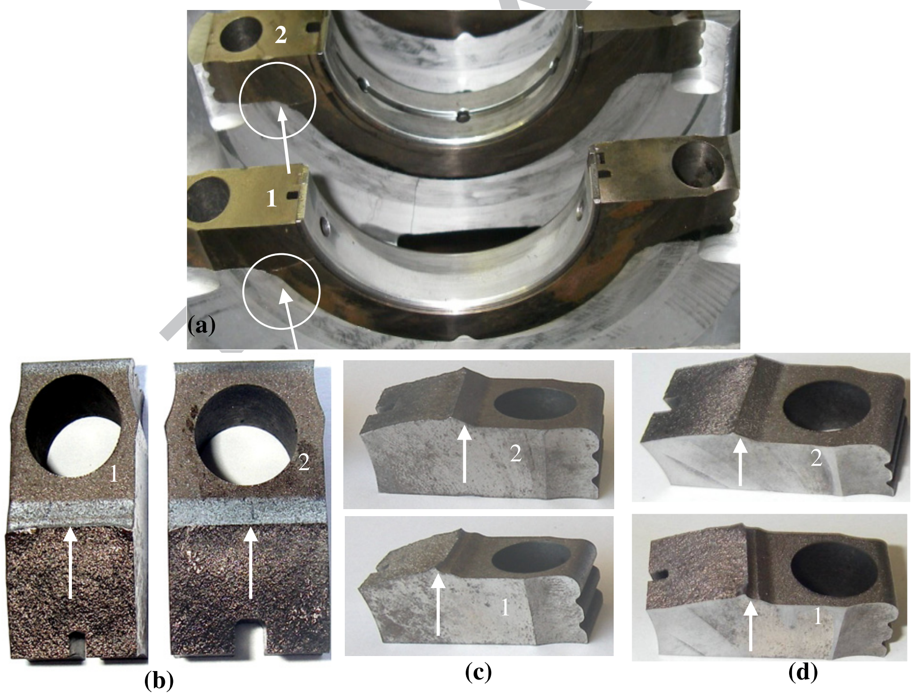


**Fig. 8.** (a) Broken material (samples) from the support steel shells; (b) crack initiation sites; (c) and (d) the two samples No. 1 and No. 2 at different positions, showing the zones without smooth concordance radius.

The fracture at the crankpin-web fillet No. 6 happened by a fatigue process as result of an alternating bending, due to the weakness of two bedplate bridges. At the crankpin the effect of torsion (or torque) does not exist because the crankpin has a translation and not a rotating movement, existing alternating bending (mode I) [9]. Shear stresses (mode II) are also present because the connecting rod force acting on the crankpin, however they can be neglected.

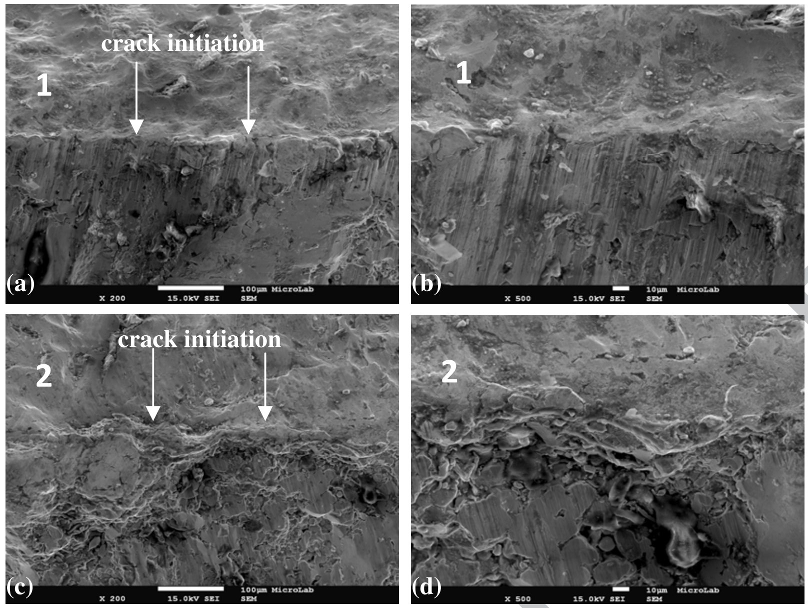


**Fig. 9.** (a) and (b) SEM micrographs showing sample No. 1; (c) and (d) SEM micrographs showing sample No. 2.

It is clearly shown that fatigue is the dominant mechanism of failure. All fractured parts resulted from the weakness of two main journal bearings as a consequence of the crack initiation on back side of the support steel shells and cracking of the bedplate bridges. During this fatigue process and after failure of steel shells, the bedplate bridges came under cyclic bending, with significant amplitude level, until the complete fracture. As result the crankshaft suffered an amplitude bending increasing which is also shown by the ratchet marks left on the crack initiation zone, see Fig. 4 (c).

The boxer motor failure presents a poor design of the steel shells back side and bedplate bridges. If the manufacturer correct the geometry of steel shells and also reinforce the bedplate bridges structure, the problem can be overcome.

## Conclusions

A failure crankshaft of a boxer diesel motor was analyzed. Fatigue is the dominant process of all fractured parts and alternating bending the main mechanism. Material defects or any misalignment of main journal bearings were not found. The surface crack has nucleated on crankpin-web fillet No. 6 but the root cause was the weakness of two central steel shells and bedplate bridges that has yielded by cracking. The crankshaft bending amplitude increases from the weakness of cracked steel shells and also the bridges of the bedplate which are beneath them. The catastrophic failure of crankshaft seems to be a consequence of poor design of steel support shells and bedplate bridges. If the manufacturer improve the design this issue will be solved.

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Highlights:

Failure mode analysis.

Crankshaft failure due to bedplate weakness.

Crankshaft failure of a boxer diesel engine.

Stress concentration on crankpin-web fillets.

Crankshaft failure mechanisms.