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Case study

Failure analysis of mixed mode crack growth in heavy duty truck frame rail

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ABSTRACT

A failure analysis investigation was performed on a fractured heavy duty truck frame rail obtained during endurance track testing. The fracture observed was on the frame web within the torque rod connection to the rear drive axle of the vehicle. This section of frame experiences multi-axial loading conditions including out-of-plane bending, twisting and shear under road loads. Metallographic examination revealed micro-cracks on the edges of an open hole located in an area of high stress concentration. This manufacturing defect acted as a stress raiser and resulted in fatigue crack initiation. Simulation of crack growth on frame rail using dynamic loads from a full vehicle model was completed. After careful analysis it was concluded that the failure occurred due to an aggressively drilled open hole which created small crack initiations in a high stress-state location of the frame. This resulted in extensive curvilinear crack growth under dynamic loads of the vehicle.

1. Introduction

A failure in a heavy duty truck frame generally involves crack growth under mixed mode I/II/III loading since the vehicle loads are highly nonlinear transient and multi-axial with large deformation behavior. This is similar to many mixed mode crack growth problems reported in literature [1–9]. The propagation of cracks in truck frame members is important to be well studied since on reaching critical crack lengths it can lead to complete breakdown of the vehicle and this may lead to catastrophic accidents with loss of life. Although there are routine vehicle inspections currently in place to detect and repair/replace fatigue cracked components, the ability to better predict crack path and orientation under various loading conditions can help avoid expensive losses and improve the design with better durability.

In this work, failure analysis of frame rail crack was carried out. Through careful macroscopic and microscopic observations, the crack was found to be primarily caused due to aggressively drilled open-hole close to an existing bolt hole. The drilled hole created small crack initiations within a high stress location of the frame. FRANC3D crack growth simulation tool combined with NASTRAN finite element solver was used in this work to simulate frame crack growth under full vehicle dynamic loads. The simulation results obtained showed good correlation to physical crack path and cycles to failure.

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2. Experimental procedure

Depending on the operational class to which the vehicle is used different testing events are selected. Fig. 1 provides schematic representation for some of the endurance test events used for full vehicle validation.

Endurance testing is done at different speeds and at different gross vehicle weight rating (GVWR). These test events provide dynamic interactions between different vehicle modules and sub-systems, enables dynamic interference and clearance check. The test vehicle will be instrumented with strain gages, load transducers and accelerometers to measure vehicle response during testing. The data measured (strain, displacement and acceleration history) are used to validate new designs and improve numerical model development. The damage obtained during test will be scaled for repeated cycles to estimate cycles to failure. The accelerated damages and wear obtained on different vehicle parts are then inspected and studied to follow up with design modifications.

3. Experimental results

3.1. Visual inspection

During a full vehicle endurance test repeated inspections were carried out after every few cycles of testing, after certain test cycles frame fatigue cracks were noticed during inspection near the rear drive axle torque rod connection of the vehicle. Fig. 2(a) shows the layout of the vehicle and the area of failure noticed on the vehicle. In Fig. 2(b), the torque rod bracket attachment to the inner web of frame with a reinforcement plate is shown. There were visible cracks on the frame extending behind the reinforcement plate and on either side of the torque rod bracket. In Fig. 2(c), the reinforcement plate bolted on both inner and outer section of frame was removed to view the crack path. This shows a bolt–hole being drilled near an existing bolt and cracks originating from this location.

Fig. 3(a) reveals the complete range of failure with the crack path taking a curvilinear route behind the reinforcement plate and multiple cracks originated at the open drilled hole. It was observed there were two open holes present close to bolted holes and the presence of open holes were not realized during testing with the reinforcement plate installed. The open hole in the middle did not seem to affect the crack growth and was observed to be present in a low stress area. A closer view of exposed crack surfaces shows primary and secondary failure origins in Fig. 3(b). In Fig. 3(b), beach marks were identified and this indicated a fatigue failure mechanism.

3.2. SEM observation

Fig. 4 shows primary crack initiations originated at the edge of the bolt hole and the secondary crack initiations originated on the inner surface of the frame adjacent to the bolt hole. In Fig. 5(a), a low magnification SEM image shows the beach marks (above the red dashed lines) indicative of a fatigue crack growth mechanism. Fig. 5(b) shows higher magnification optical micrograph image of the cracks on the bolt–hole wall which resulted from the aggressive hole drilling process.

A chemical analysis was performed on the frame section using an Optical Emission Spectrometer (OES). The chemical composition of frame section was found to be consistent with the test requirement. The base metal hardness of the frame section was found to be 32 HRC in rockwell hardness, which was in the reasonable hardness range for quenched and tempered low carbon/manganese/boron steel.

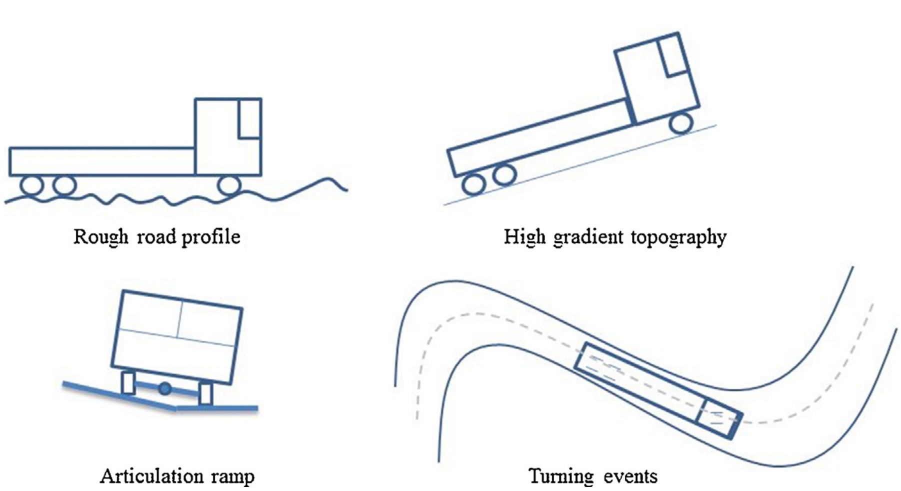

Fig. 1. Full vehicle endurance test events.