Shear fracture of jointed steel plates of bolted joints under impact load

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Abstract. The present study is concerned with the development of a fracture criterion for the impact fracture of jointed steel plates of bolted joints used in a car body, which contributes to crash simulations by CAE. We focus our attention on the shear fracture of the jointed steel plates of lap-bolted joints in the suspension of a car under impact load. Members of lap-bolted joints are modelled as a pair of steel plates connected by a bolt. One of the plates is a specimen subjected to plastic deformation and fracture and the other is a jig subjected to elastic deformation only. Three kinds of steel plate specimens are examined, i.e., a common steel plate with a tensile strength of 270 MPa and high tensile strength steel plates of 440 and 590 MPa used for cars. The impact shear test was performed using the split Hopkinson bar technique for tension impact, together with the static test using a universal testing machine INSTRON 5586. The behaviour of the shear stress and deformation up to rupture taking place in the joint was discussed. The obtained results suggest that a stress-based fracture criterion may be developed for the impact fracture of jointed steel plates of a lap-bolted joint.

1. Introduction
In the vehicle industries collision safety and reliability of cars under impact loading become more and more important in recent years, together with weight saving. The present study is concerned with the development of a fracture criterion for the impact fracture of jointed steel plates of bolted joints used in a car body, which contributes to crash simulations by computer-added engineering (CAE). For the accurate prediction of crash characteristics of car bodies by CAE, it is also necessary to examine the strength and failure of bolted joints subjected to impact loads, together with those of welded joints such as spot welds and tailored blank welds. The present study concentrates on the impact behaviour and fracture of connected steel plates of lap-bolted joints used in cars. There has been much work on bolted joints used in machine elements, in which loosening processes and tightening torque of bolted joints are investigated in detail [1][2]. However there remain many uncertainties in the impact
behaviour and fracture of bolted joint parts. In particular, we can hardly find investigations regarding the fracture of jointed steel plates of lap-bolted joints under impact loading.

In this study the impact behaviour and fracture of jointed steel plates of lap-bolted joints used in cars are examined by experimental and numerical simulation. The object is the parts of lap-bolted joints connecting the suspension frame and the bracket of the suspension frame rear mounting in a car. They are modelled as a pair of two steel plates connected by a bolt. One of the plates is a specimen subjected to plastic deformation and fracture and the other is a jig subjected to elastic deformation only. Attention is given to the impact shear deformation and fracture of the specimen plate, even though the actual behaviour of the bolted joint is complicated. Three kinds of steel plate specimens are examined, i.e., a common steel plate with a tensile strength of 270 MPa rank and high tensile strength steel plates of 440 and 590 MPa rank used for cars. The jig plate is made of high tensile strength steel of 980 MPa rank in order to make sure that the shear fracture occurs only in the specimen plates. The impact shear test of the specimens was performed using the Split Hopkinson bar technique for tension impact, together with the static test using a universal testing machine INSTRON 5586. The variation of stresses with time and the fracture characteristics in the specimen plates jointed by a bolt were measured and examined. This paper reports only about the bolted joints in hand-tightened, even though the experiments under other fastening conditions of bolted joint, such as torque and axial force, were carried out [3], [4]. The obtained results suggest that a stress-based fracture criterion may be developed for the impact fracture of jointed steel plates of a lap-bolted joint.

2. Lap-bolted joints

Although the actual fracture of lap-bolted joints in cars on collision is complicated, it might be classify into shear fracture and extraction of a bolt from the members [3][4]. The shear deformation and fracture of the specimen steel plate jointed by a bolt under impact loadings are focused on in this study. First, the static tests are conducted to obtain the static characteristics of the specimen of lap-bolted joints. Figure 1 shows a lap-bolted joint specimen with a M6 bolt used in the tests. Figure 2 shows the configuration of the specimen made of steel sheet with a tensile strength of 270 MPa (CR270) and high tensile strengths of 440 MPa (CR440) and 590 MPa (CR590) used for a car body. The jig plate is made of a high tensile strength steel of 980 MPa (CR980). The thickness of CR270 plate is 2.0 mm and the thickness of CR440, CR590 and CR980 plates is 1.2 mm. In both static and impact tests the specimen plates are plastically deformed and finally ruptured under loadings, while the jig plate remains within elastic. In Figure 2 the letter “e” denotes the distance between centreline of a joint and the end of a jointed steel plate. Three kinds of e (6.0 mm, 7.5 mm and 9 mm) were used in the tests. The static test was done using a universal testing machine INSTRON 5586 with a cross-head speed 0.01 mm/s.

Figure 3 shows the static stress-strain diagrams of the four kinds of steel plates used in the present experiments.

Figure 1. Lap-bolted joint specimen.  
Figure 2. Dimension of steel plate specimen.
Figure 3. Stress-strain diagram for four kinds of steels in static tensile tests.

Figure 4. Load ($F$)-displacement ($u$) diagram of CR440 for each $e$ in static tests.

Figure 4 shows the curves of load ($F$) versus displacement ($u$) of CR440 steel plates obtained by static shearing tests. It may be seen that the shearing loads increase with increasing $e$. The similar diagrams are also obtained regarding the plates of CR270 and CR590.

3. Impact experiments

3.1 Apparatus of impact experiments and procedure

The measurement for impact tests was performed using the vertical type of modified split Hopkinson tension bar [3]. The schematic diagram of the apparatus is shown in Figure 5.
Both input and output bars are made of SUS304 stainless steel and have the same diameter of 25.0 mm and length of 4000 mm. The Young’s modulus of the bars is 194 GPa, the mass density is $7.76 \times 10^3$ kg/m$^3$ and the velocity of elastic wave is $5.02 \times 10^3$ m/s. The steel striker tube, 42.7 mm in outside diameter, 35.5 mm in inside diameter and 2000 mm in length, was dropped from 4.0 m in height (impact velocity is about $V=8.85$ m/s). Two semiconductor strain gages (KYOWA, KSP-2-120-E4) were glued at three locations axial-symmetrically to capture the stress waves. The signals from the strain gauges were passing through the bridge boxes and amplifiers (KYOWA CDV-700A), and recorded by a digital oscilloscope (Nicolet INTEGRA10) with sampling time of 1 $\mu$s. The fastening method of bolted joint specimens to the Hopkinson bar is illustrated in Figure 6.

The displacement $u$, the rate of displacement $\dot{u}$ and the load $F$ were calculated by Equation (1), following the Hopkinson bar theory [3].

$$u = \frac{1}{\rho c} \int (\sigma_i - \sigma_r - \sigma_t) \, dt \quad \dot{u} = \frac{1}{\rho c} (\sigma_i - \sigma_r - \sigma_t) \quad F = \frac{A}{2} (\sigma_i + \sigma_r + \sigma_t)$$

(1)

Here $\sigma_i$ is the incident stress wave propagated to the input bar, $\sigma_r$ is the reflected stress wave to the input bar and $\sigma_t$ is the transmitted stress wave propagated to the output bar. And $\rho$ is the mass density, $c$ the elastic wave velocity, $A$ the cross-sectional area of input and output bars.

Figure 7(a) and (b) show the curves of impact load ($F$)–displacement ($u$) for CR270 and CR440 obtained by the impact tests, which were calculated from Equation (1). The vibration on the load waves seems to be caused by the propagation of complicated stress wave in the specimen of an lap-bolted joint that assembled four kinds of elements, namely, a testing steel plate, a jig plate, a jointed bolt and washers. The impact loads increase with increasing of the value of $e$, same as in static tests. The fractured steel plate specimens of CR270 after the impact test are shown in Figure 8.

Figure 7. Load-displacement diagrams for each $e$ in impact tests.

Figure 8. Fractured specimens of CR270.

Figure 9. Variation of impact loads with time in measured and numerical results.
3.2 Transformation of impact loads into stresses

Numerical simulations were carried out for CR270 using a FEM code LS-DYNA in order to understand the fracture mechanism of jointed steel plates of lap-bolted joints under impact loadings in the previous paper [3], [4]. Figure 9 shows the variation of impact loads with time that was measured at the gauge 2 on the output bar, and a corresponding numerical simulation. The simulation may approximate the vibration on load waves observed in impact tests. Figure 10 shows the simulated, sequence distributions of impact shear stress $\tau_{\text{yx}}$. The deformation process presented in Figure 10 is compatible with the experimental results shown in Figure 8. From consideration of the numerical simulation and the configuration of fractured specimens after impact tests, the shearing fracture process seems to be dominant, and then the area of shearing cross section, $A$, illustrated in Figure 11 is assumed to normalize the impact loads into shearing stresses [3], [4], [6].

Figure 12 (a) and (b) show the relations of $(F/A)$ and $(u/e)$ of CR270 and CR440 for each $e$, which correspond to Figure 7(a) and (b), respectively. For the sake of convenience, we should refer to the shearing stress and the moving ratio as $(F/A)$ and $(u/e)$, respectively. It may be seen that the three curves of the shearing stress and the moving ratio become similar to each other in spite of the difference of $e$ values. The same relationship is also obtained in the static results.

Figure 13 shows the relation of the shearing fracture loads and the distance $e$ obtained in the present static and impact tests. The outline marks denote the static fracture loads, while the filling marks the impact fracture loads. The fracture loads increase with increasing of $e$ and the impact results increase...
4. Concluding remarks

The behaviour and fracture of jointed steel plates of lap-bolted joints used in the suspension parts of cars are examined in static and impact experiments. In this study the shear deformation and shear fracture of the testing specimen plates are considered, even though the actual behaviour of the bolted joint parts is complicated. The specimens are made of three kinds of steel plates used for a car body. The impact shear test of the specimens was performed using the Split Hopkinson bar technique for tension impact, while the static test was done using a universal testing machine INSTRON 5586.

The shearing fracture loads increased with increasing of the distance $e$ between centerline of a joint and the end of a jointed steel plate in both of static and impact tests. And the impact fracture loads increased by comparison with the static ones due to the effect of strain rate. However, the shearing strength, defined in this study, became much the same for each steel plate regardless of the difference of $e$. This fact suggests that a stress-based fracture criterion may be developed for the impact shearing fracture of jointed steel plates of a lap-bolted joint.

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