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CRASHWORTHINESS ASSESSMENT OF SIDE IMPACT OF AN AUTO-BODY WITH 60TRIP STEEL FOR SIDE MEMBERS

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ABSTRACT–This paper is concerned with the energy absorption efficiency of auto-body side structures for the conventional steel and 60TRIP high strength steel. In order to evaluate the energy absorption efficiency, the dynamic crash analysis is carried out with the regulation of US-SINCAP. The analysis adopts the Johnson–Cook model for the dynamic material properties, which have been obtained from dynamic material tests. For the sake of the dynamic material properties, the analysis has been accurately performed for the crashworthiness assessment. The analysis result provides deformed shapes, amounts of penetration and accelerations at several important points during crash. The result confirms that 60TRIP greatly improves the crashworthiness of the side members without sacrificing the weight and thus can be used for the light-weight design of an auto-body.

KEY WORDS : Crashworthiness, Side impact analysis, TRIP Steel, Johnson-Cook model

1. INTRODUCTION

The structure of an auto-body is designed to efficiently absorb the kinetic energy during the car crash. This function is critical when the side impact is considered since there is no buffer space between the door and the passenger. In order to improve the crashworthiness of the side members, there might be two ways; one is to make the structure stronger with more members, and the other is to do with stronger materials. While the former needs redundant materials and sacrifices the light-weight design, the latter can achieve the light-weight design with the improved crashworthiness. The crashworthiness of the side members is generally evaluated with the amount of penetration as well as the shape of the center pillar and the side sill after crash. In order to reduce the risk of serious and fatal injury to passengers in side impact crashes, the regulation for the side impact crash such as FMVSS 214 and EU Directive 96/27/EC is established in each nation. Besides, national agencies also perform SINCAP (Side Impact New Car Assessment Program), NCAP, OFFCAP and other rigorous tests on cars being sold domestically, and the test results are made public to help people decide which safe automobile to purchase is.

The light-weight design of auto-body structures becomes an important issue in the automotive industry for the purpose of increasing the fuel efficiency and satisfying the emission gas regulation of vehicles. In order to achieve the weight reduction of an auto-body, the crash analysis has to be accurately conducted for prediction of the crash behavior and calculation of the impact energy absorption. For good performance of the impact energy absorption as well as the fuel efficiency, structures of an auto-body generally constructed with the low-carbon steel sheet of deep-drawing quality are being replaced by the high strength steel sheet as well as aluminum alloy sheet for weight reduction of an auto-body (Nakanishi et al., 1998; Yoshitake et al., 1998). Nowadays, many researchers have actively studied TRIP (Transformation Induced Plasticity) steel which is one of the high strength steel that satisfies the high strength as well as high formability to easily make components of various shapes (Huh and Kang, 2002; Iwamoto et al., 1998; Ojima et al., 1998). TRIP steel has the characteristics that the elongation ratio and the strength increase as the phase of retained austenite transforms into the phase of martensite during deformation.

In this paper, the crashworthiness of the side impact has been estimated for the conventional steel SPCC and

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the 60TRIP high-strength steel. The finite element analysis is performed with the regulation of US-SINCAP for the auto-body in which the center pillar and the side sill are replaced by the 60TRIP steel. The Johnson–Cook model obtained from dynamic experiments is imposed on the analysis for the dynamic response of auto-body structures (Kang et al., 1999; Huh et al., 2002) since the dynamic analysis provides more accurate results than the static analysis that has been generally adopted in dynamic simulation (Mahadevan et al., 2000; Kang and Huh, 2000). Simulation results provide the deformed shape, the acceleration at the opposite side floor of the vehicle which is being struck and amounts of penetration of the center pillar and the side sill in order to investigate the effect of the 60TRIP high-strength steel replacing the conventional steel SPCC on the crashworthiness of a vehicle.

2. SIDE IMPACT ANALYSIS

2.1. Side Impact Regulation

A schematic test configuration of FMVSS 214 is shown in Figure 1 (NHTSA, 1990). The dynamic test simulates the 90° impact of a striking vehicle traveling with the speed of 48.3 kph (30 mph) into a target vehicle traveling with the speed of 24.2 kph (15 mph). This test is achieved by a moving deformable barrier (MDB) whose four wheels rotated 27° from the longitudinal axis and impacts a stationary test vehicle with the closing speed of 54 kph (33.5 mph). For a typical passenger car, the left edge of the MDB is 940 mm forward of the mid point of the struck vehicle wheel base.

The MDB has a total mass of 1367 kg. The aluminum honeycomb of the barrier face is specified by design. The

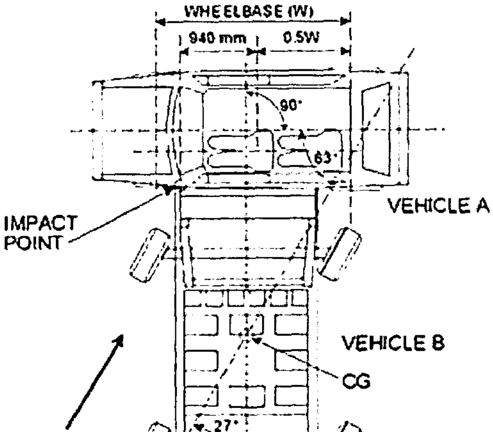


Figure 1. Side impact test configuration of FMVSS 214.

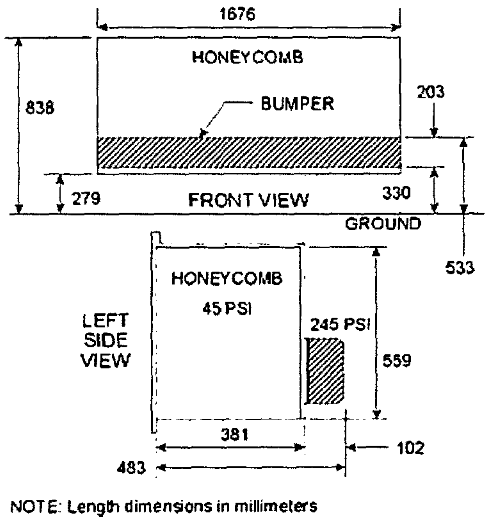


Figure 2. Schema of a moving deformable barrier.

bottom edge of the MDB is 279 mm from the ground. The protruding portion of the barrier simulating a bumper is 330 mm from the ground. The dimensions and material characteristics of the MDB face are shown in Figure 2. This was initially modeled from the weights of passenger cars and light trucks in the U.S. fleet with an adjustment made assuming a downward trend in vehicle mass due to fuel economy needs. Side impact dummies are placed in front and rear occupant positions on the side of the vehicle that is being struck. Crashworthiness can be estimated from the acceleration at various points of dummies and loads. In this paper, dummies are beyond our scope and not considered in the present analysis. Side impact analysis is performed with the regulation of US-SINCAP that is stricter than FMVSS 214. The velocity of the MDB of US-SINCAP is 38.5 mph while other conditions are same as FMVSS 214.

2.2. Side Impact Model

The finite element model using the side impact analysis is shown as Figure 3. The analysis model has a length of 4200 mm, a width of 1700 mm, a height of 1400 mm and a total mass of 990 kg. The model of an auto-body is composed with 79,000 shell and 290 beam elements, and the model of the MDB is made up of 8,000 solid and 620 shell elements. The side impact analysis is performed with the regulation of US-SINCAP using LS-DYNA3D (LSTC, 1999). The crashing time after collision is 70 msec and the time elapsed for calculation is about 24 hours in the HPC320 system.

The Johnson–Cook model considered dynamic behavior of materials is imposed on the analysis (Johnson and Cook, 1983). The Johnson-Cook model is represented by equation (1).

$$\bar{\sigma} = [A + B\bar{\varepsilon}^n][1 + C\ln\dot{\bar{\varepsilon}}][1 - T^{*m}] \quad (1)$$

where T^* is the homologous temperature represented by equation (2).

$$T^* = \frac{T - T_{room}}{T_{melt} - T_{room}} \quad (2)$$

where T is the temperature of the specimen, and T_{melt} is the melting temperature of the specimen. The first term bracketed in the equation (1) is the strain hardening term; the second is the strain-rate hardening term; and the third is the thermal softening term. In the Johnson–Cook model, the stresses at the strain rate of 1/sec and higher levels are linearly interpolated in the logarithmic scale. Coefficients of the Johnson-Cook model is obtained from experiments using the tensile testing machine and the tension split Hopkinson bar (Kang et al., 1999; Huh et al., 2002). The material constants for the conventional steel SPCC and the 60TRIP steel are tabulated in Table 1.

Figure 4 shows stress-strain curves of the conventional steel SPCC and the 60TRIP steel at the strain rate of 1/sec. The 60TRIP steel has higher flow stress and larger work hardening especially just after the yielding than SPCC steel because the TRIP steel transforms retained austenite into martensite during deformation. The work hardening exponent of the 60 TRIP is, however, smaller than that of the SPCC, since the initial yield of the 60 TRIP is quite larger than that of the SPCC. The work hardening exponents of two materials are larger than the normal value because the tensile test was carried out at the strain rate of 1/sec.

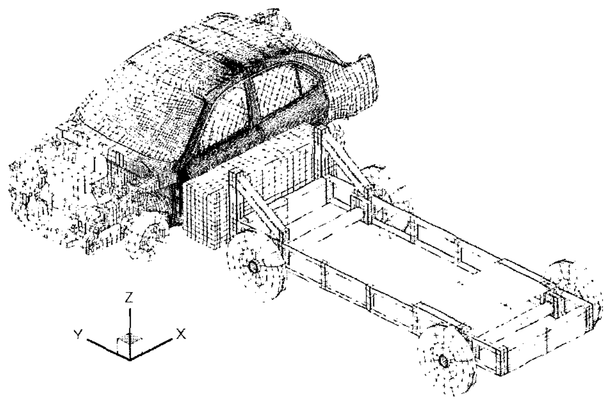


Figure 3. Finite element model for side impact analysis.

Table 1. The material constants for the conventional steel SPCC and the 60TRIP steel.

Material	A (MPa)	B (MPa)	n	C	m
SPCC	273.2	376.3	0.567	0.04	0.55
60TRIP	458.9	787.8	0.472	0.024	0.36

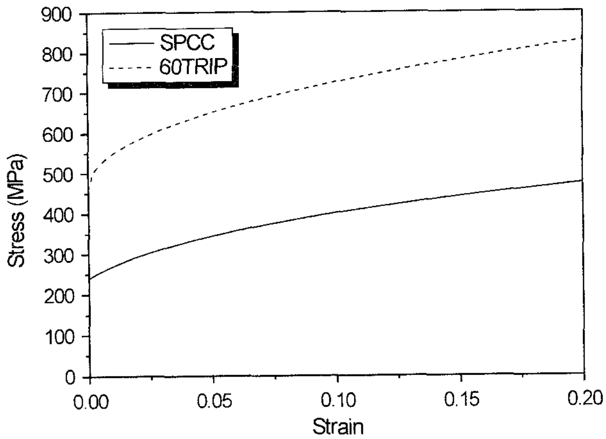


Figure 4. Stress-strain curves of 60TRIP steel and the conventional steel SPCC at the strain-rate of 1/sec.

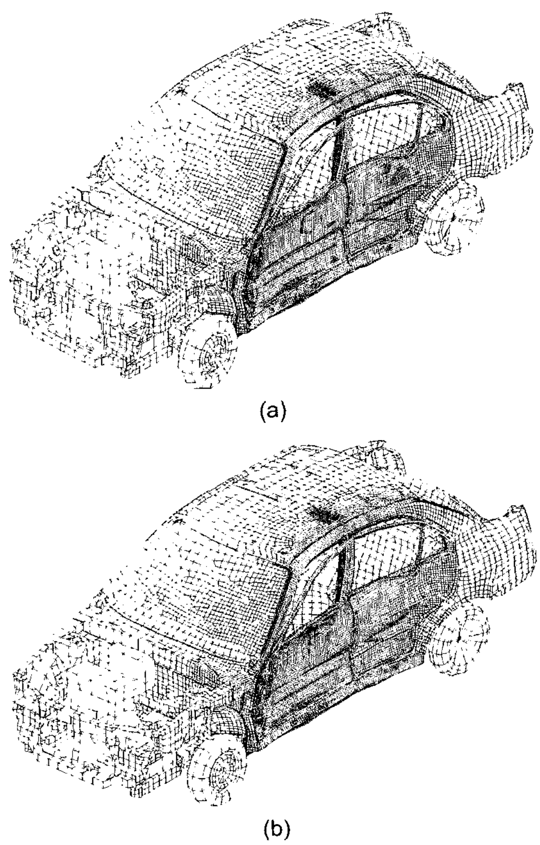


Figure 5. Deformed shapes of an auto-body with the conventional steel SPCC: (a) after 35 msec; (b) after 70 msec.

3. RESULTS OF THE SIDE IMPACT ANALYSIS

In this paper, the crashworthiness of the side impact has been evaluated for the conventional steel SPCC and the 60TRIP high-strength steel. The finite element analysis is performed with the regulation of US-SINCAP for the model in which the center pillar and the side sill are replaced by the 60TRIP steel.

Deformed shapes of an auto-body with the conventional material at 35 msec and 70 msec after collision are shown in Figure 5. Figure 6 is deformed shapes of an auto-body with the 60TRIP steel applied to both the center pillar and the side sill after the side impact. Deformation is concentrated at the impact side before 40 msec. After this, the increment of deformation decreases since the auto-body makes the rigid body motion. The figures show that deformation of an auto-body with 60TRIP steel is smaller than that with the conventional steel.

Since the deformation and the rigid body motion of an auto-body occur simultaneously after collision, the pure deformation without the rigid body motion needs to be considered for investigation of deformation behavior. The reference to remove the rigid body motion is the front door on the opposite side of the vehicle that is being struck. The X-axis, Y-axis and Z-axis are the length, the width and the height of an auto-body, respectively as explained in Figure 3. The deformation of the center

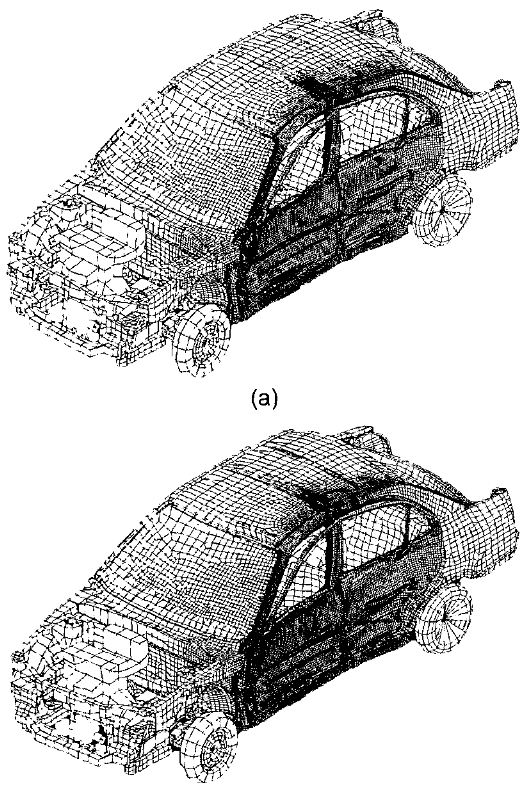


Figure 6. Deformed shapes of an auto-body with 60TRIP steel: (a) after 35 msec; (b) after 70 msec.

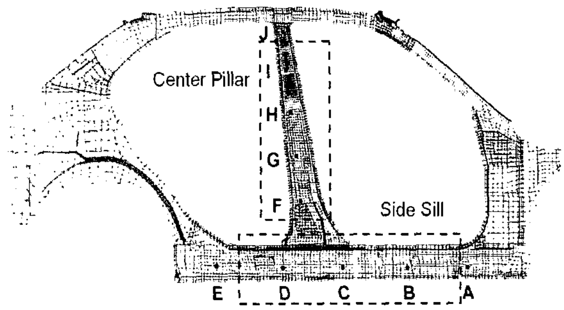


Figure 7. Location of reference points at the center pillar and the side sill.

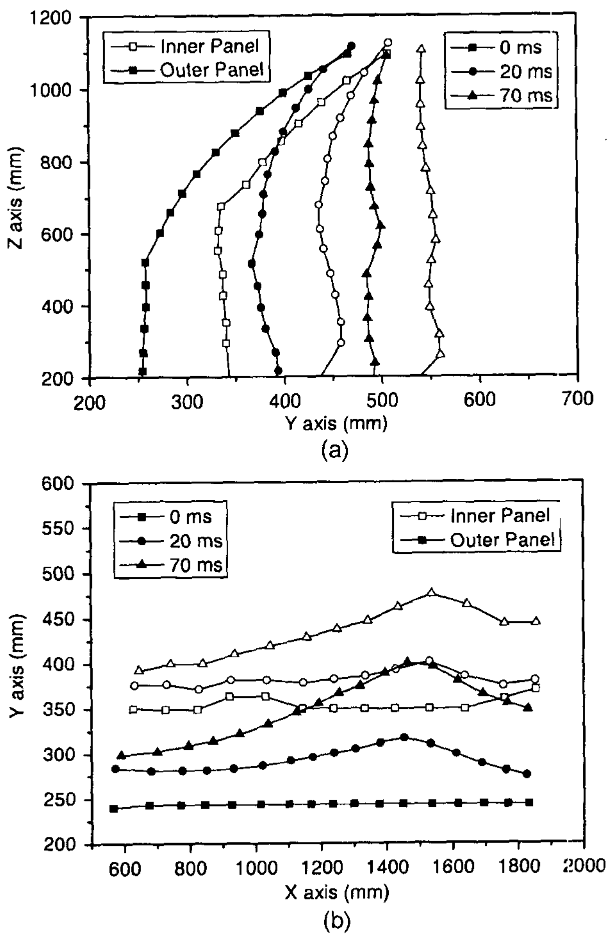


Figure 8. Deformed profile of the inner and outer panel of an auto-body with conventional steel SPCC for the US-SINCAP test: (a) center pillar; (b) side sill.

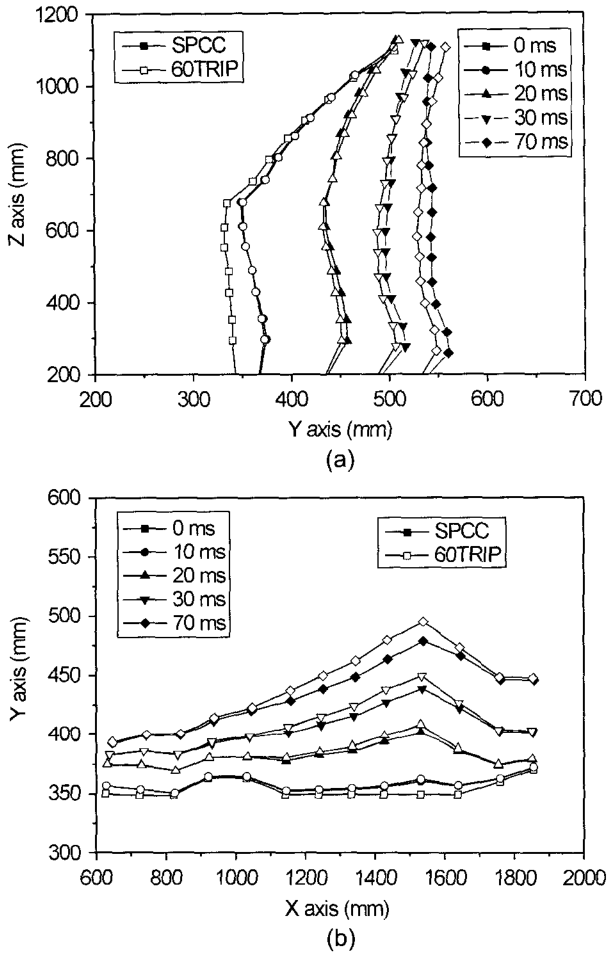


Figure 9. Deformed profile of the inner panel of an auto-body with 60TRIP steel applied to the center pillar: (a) center pillar; (b) side sill.

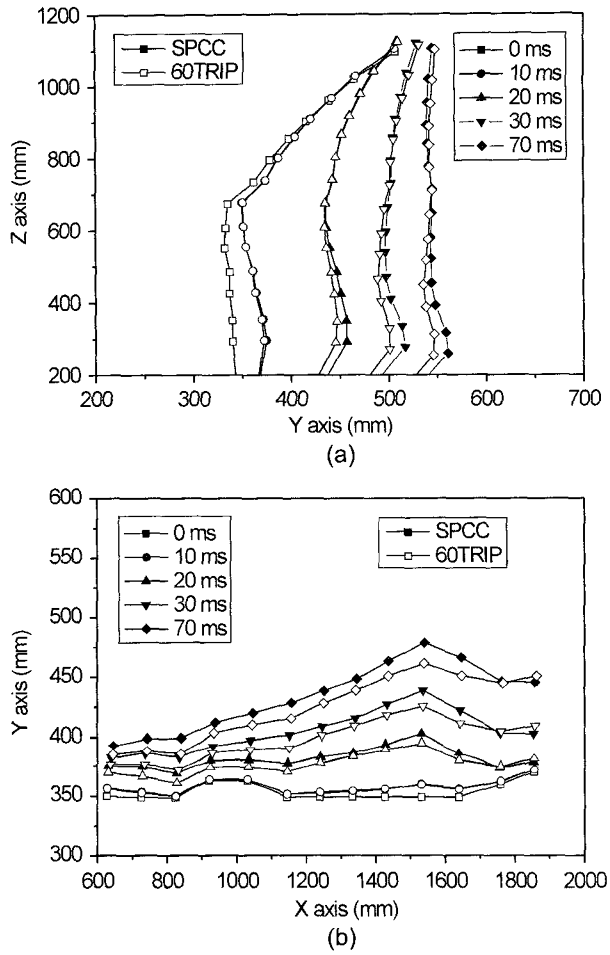


Figure 10. Deformed profile of the inner panel of an auto-body with 60TRIP steel applied to the side sill: (a) center pillar; (b) side sill.

pillar and the side sill is described at the Y-Z plane and the X-Y plane as shown in Figure 8.

Deformed profiles of the inner and outer panels of the center pillar and the side sill versus time without rigid body motion are shown in Figure 8. The tendency of deformation for the inner panel is similar to the outer panel while the outer panel deforms slightly more than the inner panel. Since inner panel directly affects an occupant in a vehicle, only the inner panel is to be considered especially in the lower region of the center pillar and the whole side sill.

Figure 9 shows deformed profiles of the inner panel of an auto-body with the 60TRIP steel applied to the center pillar without the rigid body motion. The deformation concentrates at the connecting region of the center pillar and the side sill where is colliding with the bumper of MDB. The deformation of the middle region of the center pillar decreases against the original model, but connecting parts of the center pillar with the side sill and the roof rail deform more than the original model. Once the 60TRIP steel is applied to the center pillar, the overall deformation of the center pillar decreases while deformation of the side sill increases. This phenomenon results from that the energy that the center pillar does not absorb less than the conventional model is transmitted to the side sill and the roof rail. This result means that the damage of the upper body of a passenger decreases and the safety of the side impact can be predicted to improve since the deformation of an auto-body is dispersed in the lower region.

Deformed profiles of the inner panels of side members for an auto-body with the 60TRIP steel applied to the side sill are shown in Figure 10. The amount of penetration decreases at the side sill and the lower region of the center pillar because of the increment of the strength. The amount of penetration for the upper region of the center

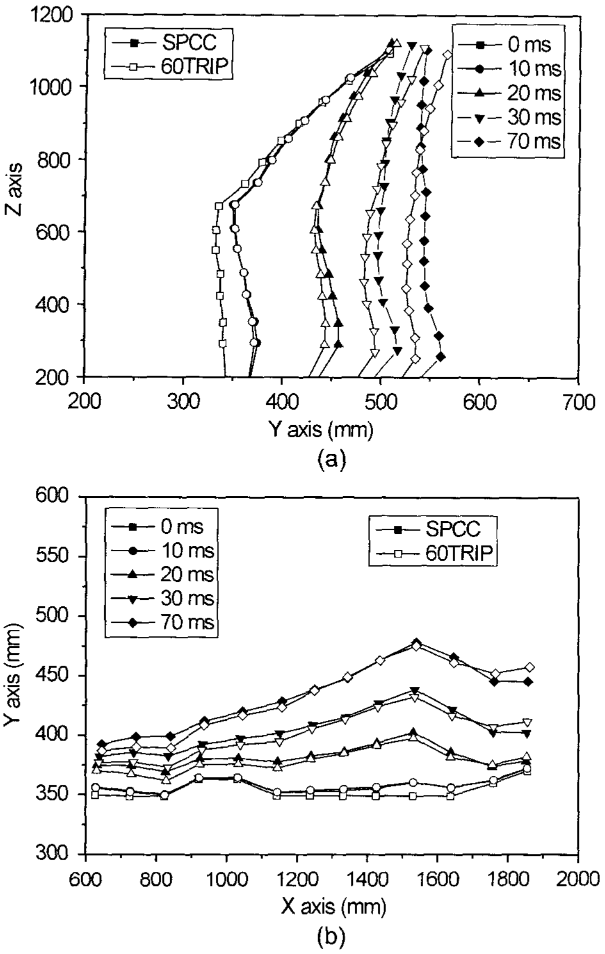


Figure. 11 Deformed profile of the inner panel of an auto-body with 60TRIP steel applied to both the center pillar and the side sill: (a) center pillar; (b) side sill.

pillar is, however, nearly identical in comparison with the original model. Adoption of the 60TRIP steel for the side sill does not affect the deformation of the center pillar and has an effect on the side sill and the lower region of the center pillar.

Figure 11 is deformed profiles of inner panels of the side member for an auto-body with the 60TRIP steel applied to both the center pillar and the side sill. This analysis result has the blending effect of the previous two cases. The deformation of the middle region of the center pillar decreases remarkably while the deformation of the upper region of the center pillar increases on the contrary since the energy that the center pillar does not absorb less than the conventional model is transmitted to the roof rail. The deformation tendency of the side sill maintains similarly in comparison with the original model.

Table 2 illustrates quantitatively the amount of penetration at the points J, G and C designated in Figure 7. When the 60TRIP steel is applied to both the center pillar and the side sill, the penetration at G, the middle region of the center pillar, decreases by 15.6 mm while the penetration at J, the upper region of the center pillar, increases by 20.8 mm than the original model.

The acceleration is traced at the point P and Q of the opposite floor to the impact side as shown in Figure 12. The acceleration at the point P is not particularly influenced by adoption of the 60TRIP steel. But the magnitude and the oscillation of the acceleration at the point Q greatly decrease as shown in Figure 13(b) when the 60TRIP steel is applied to the center pillar. Figure 14 shows that the relative velocity at the reference point H, the middle point of the center pillar as explained in Figure 7, slightly decreases and the tendency is similar to

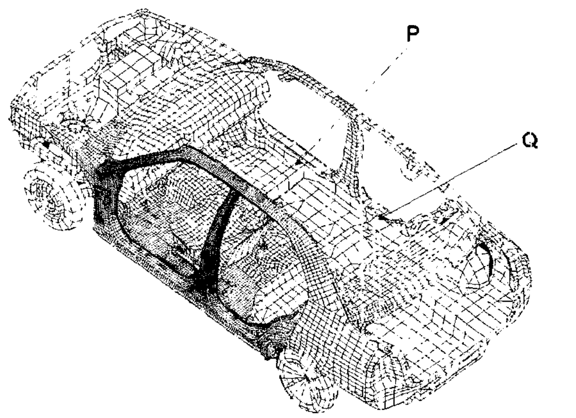
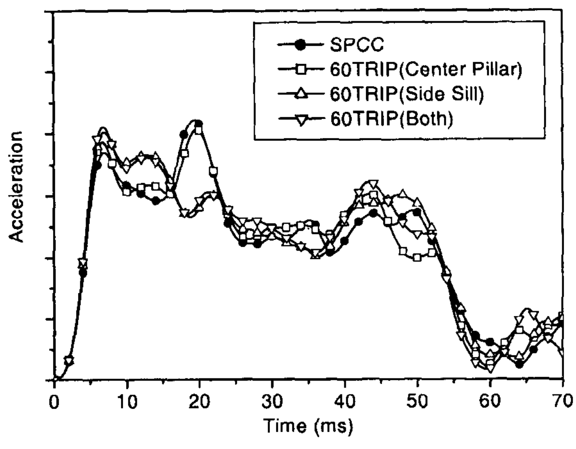


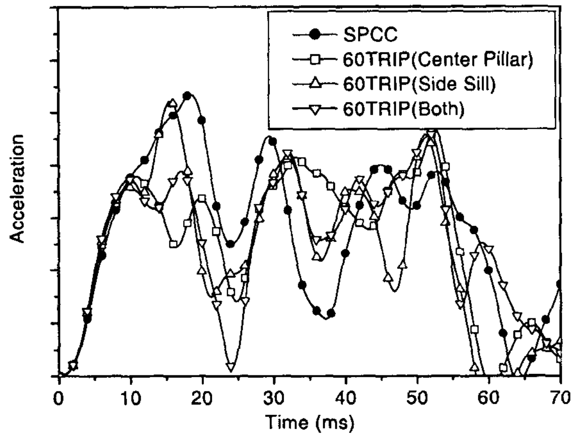
Figure 12. Tracing points for measuring the acceleration.

Table 2. The penetration at the points J, G and C after 70 msec elapsed from the crash.

Position	Penetration (mm)			
	SPCC	60TRIP for center pillar	60TRIP for side sill	60TRIP for center pillar and side sill
J	37.6	52.3	40.9	58.4
G	209.1	194.8	206.8	193.5
C	129.4	145.9	112.3	126.7



(a)



(b)

Figure 13. Acceleration at tracing points: (a) the point P; (b) the point Q.

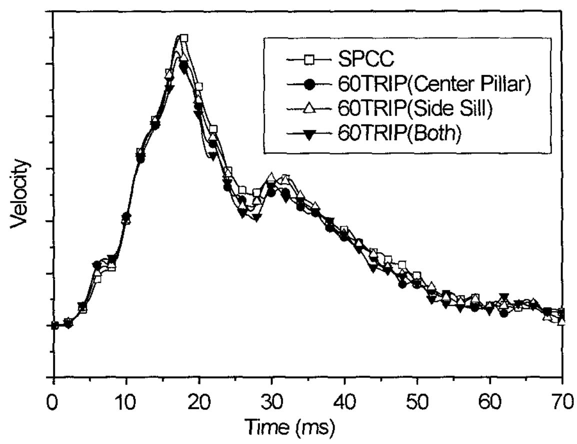


Figure 14. Relative penertrating velocity of at the point H.

the original model when the 60TRIP steel is applied to the side members.

4. CONCLUSIONS

In this paper, the crashworthiness of side impact has been evaluated for the conventional steel SPCC and the 60TRIP high strength steel. The finite element analysis is performed with the regulation of US-SINCAP for the model in which the center pillar and the side sill are replaced by the 60TRIP steel. The Johnson–Cook Model obtained from dynamic experiments is imposed on the analysis for the accurate dynamic response of auto-body structures instead of the static model that has been generally adopted in dynamic simulation. Simulation results provide the deformed shape, the acceleration at the opposite floor to the impact side and amounts of penetration of the center pillar and the side sill in order to evaluate the crashworthiness of a car.

When the 60TRIP steel is applied to only the center pillar, the overall deformation of the center pillar decreases while the connecting parts of the center pillar with the side sill and the roof rail deform more than the original model with the conventional steel. Adoption of the 60TRIP steel for the side sill does not affect the deformation of the center pillar and has an effect on the side sill and the lower region of the center pillar. In the case with the 60TRIP steel applied to both the center pillar and the side sill, the effect of the replacement becomes blending effect of the previous two cases. The deformation of the middle region of the center pillar decreases remarkably while the deformation of the upper region of the center pillar increases on the contrary. The deformation tendency of the side sill maintains similarly in comparison with the original model. When the high strength steel is applied to the center pillar, both the acceleration and the relative velocity is reduced. Since the deformation of an auto-body is dispersed in the lower region, the damage of the upper body of a passenger decreases and the safety of the side impact is predicted to improve. The result confirms that the 60TRIP greatly improves the crashworthiness of the side members without sacrificing the weight and thus can be effectively used for the light-weight design of an auto-body.

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