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Research Article

Effective Press Folding Line Process as Producing Smart Intersection in Square Steel Pipe Structures by Using Crushed Cross Section Compactly

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Abstract

As a cross section of square steel pipe is crushed, the upper plate and the lower plate deform inward, and the side plates deform outward from the original square cross section shape. When the press folding line process as deformation induction is applied, the upper plate and the lower plate keep flat, and the side plates are compactly folded inward. This deformation pattern is safe without causing any harm to the surrounding area, and makes it possible to improve impact energy absorption performance by folding side plates as overlapping. Moreover, square steel pipe structures include places as pipes intersect and places to avoid interference with other parts (piping, wiring, fork claws, etc.). In such cases, the current method is to create an opening by cutting off. At that time, the structural strength will decrease, so reinforcing materials are often installed as a countermeasure. On the other hand, if the opening is processed by laterally impact crushing using the press folding line process proposed in this paper, a crushed part will remain, suppressing the decrease in structural strength, and this can be handled without adding reinforcing material to be a smart intersection. This paper shows the findings based on experimental data, FEM (Finite Element Method) results on processing conditions for inward deforming side plates of square steel pipes and evaluation of impact energy absorption performance in laterally impact crushing.

Keywords

Press Folding Line Process, Impact Energy Absorption, Fem, Deformation Induction, Impact Crushing

1. Introduction

Structural steel pipes are widely used for guardrails, steel frame structures, mechanical structural components, etc. Depending on the application, there are general structural carbon steel pipes, general structural square steel pipes, mechanical structural carbon steel pipes, etc. Of these, general structural square steel pipes STKR400 (JIS G 3466: 2021, hereafter abbreviated as square steel pipes) [1] are widely available on the market, and are used as the experimental material in this paper.

In structures, pipe members are important components that play a role as the main frame, so there are many reports on the phenomenon of axial crushing [2-10]. However, there are few reports on cross section crushing. Among them, there is a report by Toi and Nagayama [11] on cross section crushing experiments under quasi-static loading conditions and FEM analysis. The purpose of their report [11] is to improve the

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impact energy absorption performance of steel structures when they are crushed in collision. According to their report, when a cross section of a square steel pipe is crushed in a crushing experiment, the top and bottom plate are deformed inward convexly, and the side plates are deformed outward convexly from the original square cross section shape. The cross section crushing phenomenon of square steel pipes, as shown in Figures 1(a) to (c), is generally well known, but when a steel structure is subjected to a lateral load and the cross section is impact crushed, there is a risk of damage to the surrounding area of the structure when the side plates are deformed outward convexly. In contrast, when the process method proposed in this paper is applied, the top and bottom plate remain flat, and the side plates are folded compactly inward, as shown in Figure 1(d). This type of deformation pattern is safe as it does not cause harm to the surrounding area, and is expected to improve impact energy absorption performance as the side plates are folded compactly so that they overlap. Furthermore, as shown in Figure 2, square steel pipe structures have points where square steel pipes intersect with each other and points where it is necessary to avoid interference with other components (pipes, wiring, fork prongs, etc.). In such cases, the current method is to cut-off or notch part of the square pipe to remove material and create an opening. In this case, reinforcement is often attached as a countermeasure to the reduction in structural strength caused by material removal. In contrast, if the proposed process method is applied to create the opening, the crushed part remains as shown in Figure 3, which suppresses the reduction in structural strength, and this is expected to have the advantage of not requiring additional reinforcement, can be called a smart intersection.

This paper shows, FEM analysis to carry out preliminary studies on the appropriate process conditions for deforming the side plates inward, being folded compactly in laterally impact crushing, as well as an evaluation of impact energy absorption performance, and report the findings obtained by discussing the experimental verification results and FEM results.

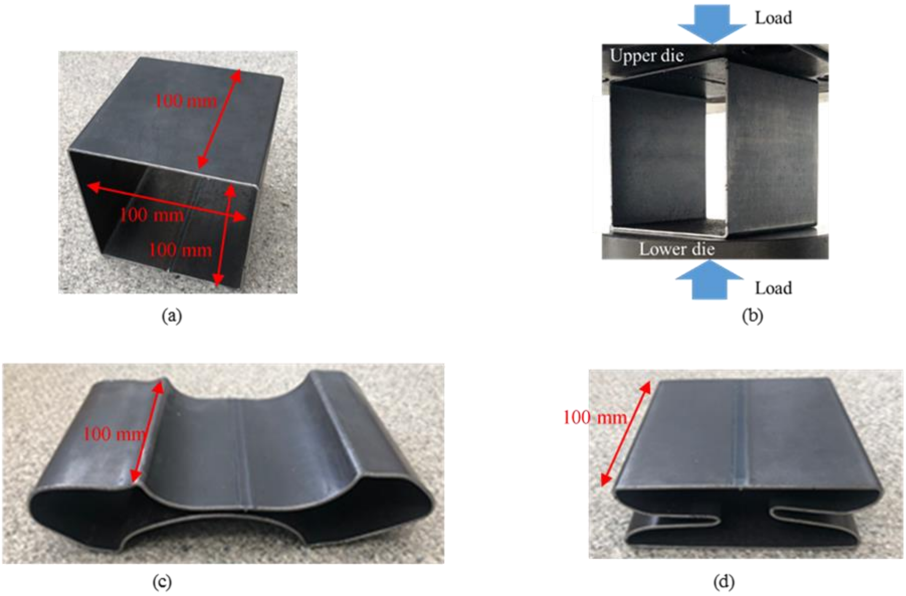


Figure 1. Typical crushed cross section deformation pattern of a square steel pipe. (a) Appearance of a general steel pipe with a plate thickness of 1.6 mm and a cross section side length of 100 mm before crushing. (b) Loading conditions during cross section crushing. (c) Crushed cross section deformation shape of a general square steel pipe (top and bottom plates deform inward, side plates deform outward). (d) Crushed cross section deformation shape after applying the proposed process method (top and bottom plate remain flat, side plates deform inward and are folded compactly).

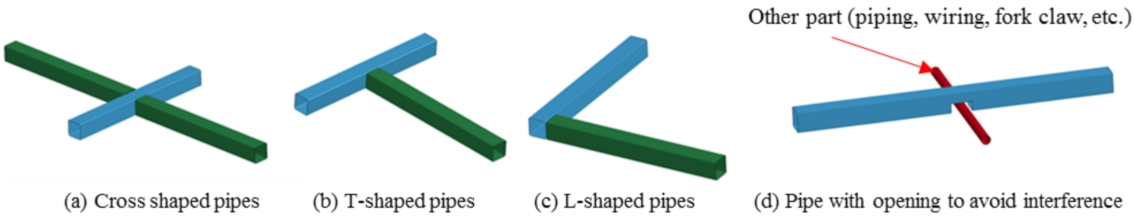
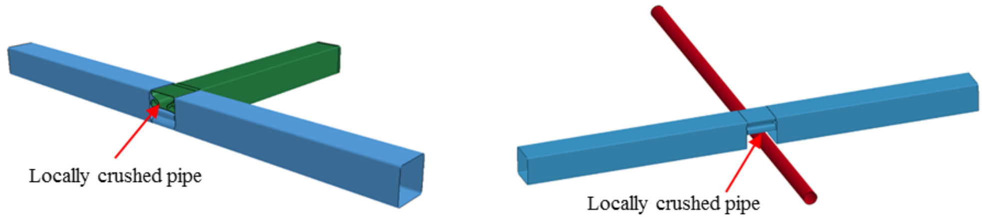


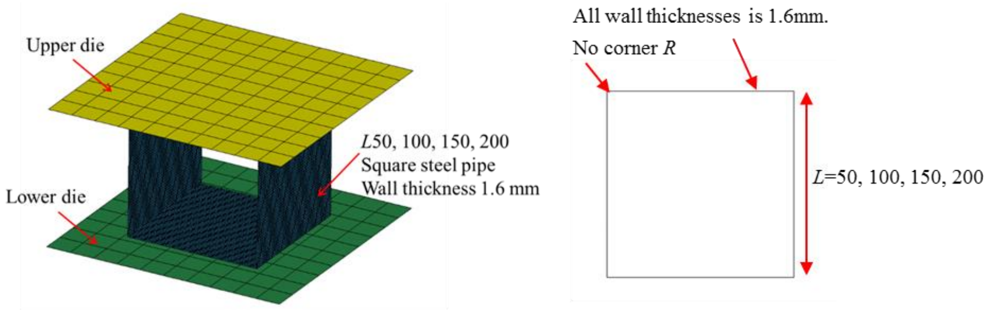
Figure 2. Structure patterns. Structures with (a) cross, (b) T, (c) L-shaped pipe intersections. (d) Structures that require avoiding interference with other parts, such as piping, wiring, or fork claws. The cut-off process is often used, with reinforcement material used to maintain struc-

tural strength.



) Proposed T-shaped pipes using locally crushed steel pipes (b) Proposed opening using locally crushed steel pipes

Figure 3. *Proposed applications.*



(a) FEM model for 100 mm long square steel pipe (b) Cross section geometry of simple virtual pipe

Figure 4. *FEM models for simple virtual square steel pipes.*

2. Preliminary Studies by Using FEM Analysis

2.1. Virtual Square Steel Pipes

The impact crushing phenomenon of the cross section of a square steel pipe is first examined by taking a simple virtual square steel pipe. The corners of the actual square steel pipe cross section are rounded. In this paper, this roundness is referred to as corner *R*, and the effect of the radius *R* value is also considered. For the virtual square steel pipe, the corner *R* is simplified to 0, and the total cross section plate thickness is constant at 1.6 mm, and the effect of the processing speed (also called the die speed) and the cross section shape on the crushing deformation pattern is investigated by FEM analysis (Figure 4). The lower die is fixed (also called the fixed die) that restricts movement up and down, left and right, and rotation, and a load die (also called the upper die). The lower part of the square pipe cross section is supported by the fixed die, and the upper part of the cross section has a load die, which are rigid bodies, and the load die moves vertically downward. Since the relationship between the vertical movement and stop of the upper and lower die is relative, the same applies even if the upper die is stopped and the lower die is changed to a role of rising vertically. The die speed is the processing speed (die speed *V*). In addition, here, it is assumed that the upper and lower die and the upper and lower plate of the square steel pipe are in uniform contact at the start of the impact, and FEM analysis of the deformation phenomenon due to uneven contact at the start of the impact is out of scope in this report.

Table 1. *Parameter constants in FEM.*

Symbol	Value
Young's coefficient E (GPa)	206
Plasticity coefficient F (Mpa)	627
Strain hardening index n (-)	0.25
Poisson's rate ν (-)	0.3
Yield stress σy (MPa)	200
Friction coefficient between plate and die μ (-)	0.1
Cowper-Symonds equation c and p	8000, 8

FEM analysis software used is LS-DYNA [12] and a dynamic explicit method is used. The dies are modeled as rigid bodies using shell elements, and the square steel pipes are modeled as an elastoplastic body using shell elements. The parameters of the Cowper-Symonds equation, the material constants, the strain rate dependency of the material and the friction coefficient with the dies are shown in Table 1. FEM analysis method is the same as the previously report [13-16]. Assuming that the cross section side length is sufficiently long compared to the cross-sectional plate thickness, the shell element size is approximately 10 to 20 mm for the dies and approximately 1 to 2 mm for the square steel pipes.

Four FEM models are created with cross section side lengths L = 50, 100, 150, and 200 mm for a 100 mm long square steel pipe as shown in Figure 4. Here, for examples, the case where L = 100 mm is abbreviated as L100 in the following. The same applies to other dimensions such as L50, L150, and L200. The number of shell elements for the L100 square steel pipe is approximately 8200. A number of FEM analyses are performed at various die speeds V in the maximum speed range of 10 m/s. V is set starting from 0.1 m/s to observe the deformation pattern of the side plate, and the die speed was changed by 1.0 m/s increments in the die speed range where the situation did not change much, and by 0.1 m/s increments in the transition range. It is found that there are speed ranges where the side plate deforms outward and speed ranges where the side plate deforms inward being folded compactly, and with a speed difference of 0.1 m/s, when the speed difference is above the critical speed V_c, the side plate deforms inward being folded compactly, and when the speed difference is below the critical speed V_c, the side plate deforms outward.

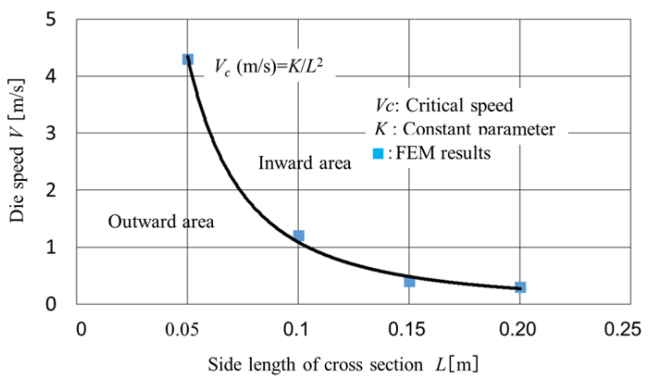


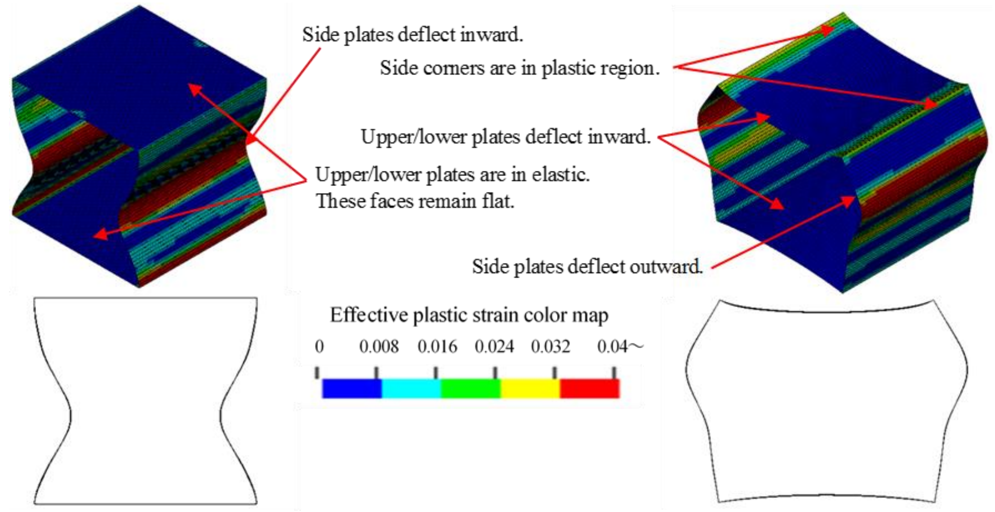
Figure 5. *Relationship between the critical velocity V_c and the cross-sectional side length L obtained from the FEM results.* *($Vc = K/L^2$, K=0.011 m^3/s)*

In Figure 5, the critical speed V_c is plotted as a blue square symbol. In the four cases, the cross section side length L of square steel pipes and V_c are approximately inversely proportional, and V_c becomes slower as L becomes longer. For examples, at the case of L100, as $V \geqq 1.2$ m/s, the side plate deforms inward being folded compactly, and as $V \leqq 1.1$ m/s, the side plate deforms outward in a convex shape. As examining the equivalent plastic strain distribution and cross section deformation shape (Figure 6) near the die displacement δ=20 mm, for a fast V of $V \geqq 1.2$ m/s, the top and bottom plates remain in the elastic region rather than the plastic region, and both the top and bottom plate are in a flat state and in complete contact with the loading die face. In this case, the side plates deform inward being folded compactly because it is easier to deform in the direction of reducing the angle (90°) with the top and bottom plates than to widen it. On the other hand, for a slow V of V=1.1 m/s or less, both side corners of the top and bottom plates reach the plastic region and deformation resistance becomes strong, so the middle region of the top and bottom plates deforms inward in a convex shape. As a result, both side plates are deformed being pushed outward. To summarize this mechanism, it can be considered that on the low-speed conditions, friction force is relatively low, so the corners of the top and bottom plates are able to move easily along the die face, causing the top and bottom plates to bend inward and the side plates to deform as being pushed outward, but on the high-speed conditions, friction force is high, so the corners of the top and bottom plates are less likely to move along the die face, so they remain flat, and the side plates deform inward, reducing the angle between the top/bottom plate and side plates, and are folded compactly.

2.2. Real Square Steel Pipes

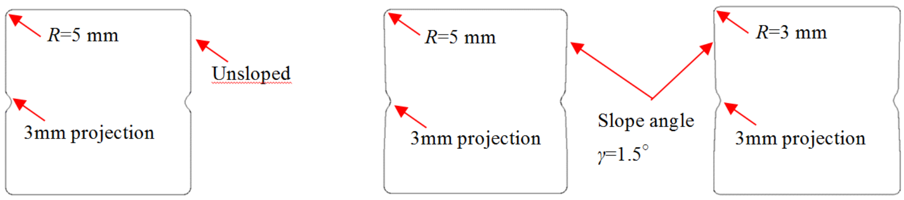
The corners of an actual square pipe cross section shape are rounded, so the deformation pattern differs from that as corner R = 0 in the previous section. As reported by Toi and Nagayama [11], the side plates deform in a direction that widens the angle (90°) with the top and bottom plate, i.e., the side plates deform convexly outward. For the side plates to deform inward, it is thought that the side plates must first be inclined inward, there must be a convex protrusion on the inward side at the center of the side plate height, and the side plate deforms inward, as V is above the critical speed V_c. From the findings in the previous section, it can be surmised that as the tip of the inward convex protrusion is further inward, V_c be lower, as it is only slightly convex, a higher V_c speed be required. This surmise should be verified by using FEM analysis. In the previous section, four FEM model cases are created with pipe cross section side lengths of L50, 100, 150, and 200, but considering ease of handling as experimental members to be set in the impact testing machine and the processing machine used in Chapter 3, L50 is too small and L150 or more is too large, so L100 (plate thickness 1.6 mm, length 100 mm) is selected and set the following three types in this report.

1. Type A: Corner R = 5 mm, the cross section shape with no inclination of the side plates, with an inward protrusion in the center in the height direction.
2. Type B: Corner R = 5 mm, the cross section shape with inward inclination, with an inward protrusion in the center in the height direction.
3. Type C: Corner R = 3 mm, the cross section shape with inward inclination, with an inward protrusion in the center in the height direction.



(a) $V \geq 1.2$ m/s (b) $V \leq 1.1$ m/s

Figure 6. *Equivalent plastic strain distributions at a stage near the die displacement δ=20 mm.*



(a) Type A (b) Type B (c) Type C

Figure 7. *Three types of cross section as FEM model.*

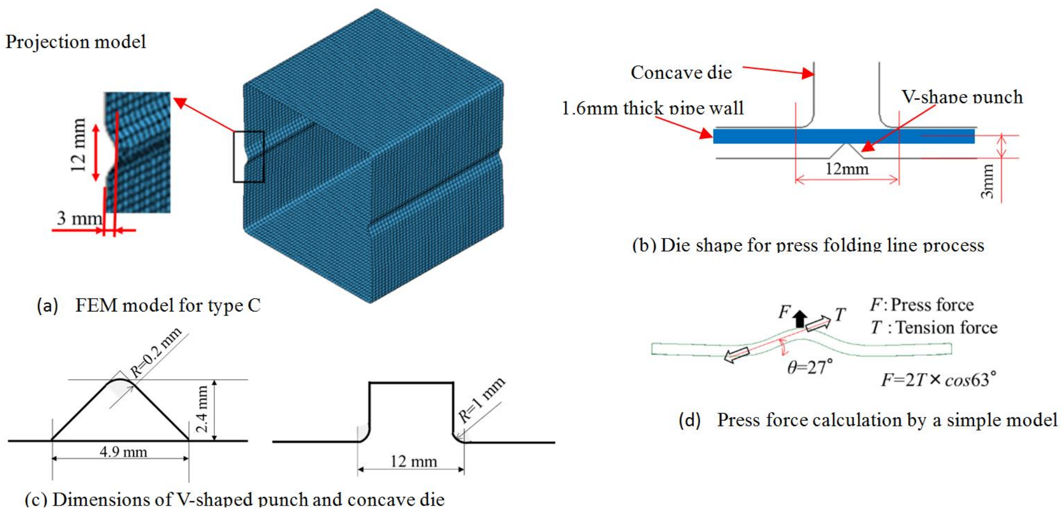


Figure 8. *FEM model for type C, die shape for press folding line process and simple model of press force.*

Figure 7 shows FEM cross section models of the above square steel pipe *L*100 (plate thickness 1.6 mm, length 100 mm, corner *R* = 3 mm and 5 mm). In JIS G 3466: 2021, the corner *R* of this size square pipe is approximately 3 mm, but two types of corner *R* values are set to investigate the influence of the corner *R* value. The height of the central protrusion on the side plate of the three types of FEM models is approximately 3 mm based on the center of the plate thickness, but the side plate of type A has no inclination, and the inward inclination angle γ of the side of types B and C is set to approximately 1.5°. The width of the protrusion at the center of the side plate (Figure 8(a)) is 12 mm. The reasoning behind setting the width dimension is explained as follows:

As the strain hardening coefficient of the mild steel material used for square steel pipes is approximately 0.3, the total deformation strain in all processes must be within 0.3. There are two processes: a press folding process using a V-shaped tool before impact crushing, and an impact crushing process. In order to keep the total deformation strain in both processes within 0.3, the design guideline is to keep each process within 0.15. When the V-shaped tool is pressed with a press load to elongate and deform into a protrusion, the deformation strain at that time is calculated using the following Equation (1) and (2). In Equation (1), the deformation strain is 0.11 when the protrusion width on one side is 6 mm, and in Equation (2), the deformation strain is 0.15 when the protrusion width is even shorter, 5 mm.

$$\text{The deformation strain when it is stretched from a length of 6 mm to } \sqrt{(6^2+3^2)} = 6.7 \text{ mm} = \ln(6.7/6) = 0.11 \tag{1}$$

$$\text{The deformation strain when it is stretched from a length of 5 mm to } \sqrt{(5^2+3^2)} = 5.8 \text{ mm} = \ln(5.8/5) = 0.15 \tag{2}$$

When the width on one side is set to 5 mm, there is no margin for the allowable strain limit, so the protrusion width is set to 12 mm (= 2 × 6 mm), the protrusion shape dimensions of the V-shaped tool are set to a right-angled isosceles triangle with a height of 2.4 mm and a tip R = 0.2 mm, and the concave shape dimensions (Figures 8 (b) to (c)) are set.

Next, the required press load F is first calculated using the simple model method shown in Figure 8 (d). The plasticity coefficient of the mild steel square pipe material is approximately 630 MPa, and the cross section area is 160 mm^2 (plate thickness 1.6 mm × length 100 mm), so the one-sided tension T = tensile stress × cross section area, then T = 630 MPa × $0.11^{0.3}$ × 160 mm^2 ≒ 52 kN. As the inclination angle θ is about 27° (=$\tan^{-1}$(3/6)), the press load F is estimated to be 2×52 kN×cos63°≒about 40 to 50 kN.

Next, a square steel pipe is modeled using solid elements as shown in Figure 9(a), and the relationship between the press load F and the side plate inclination angle γ after springback is investigated by using FEM analysis. The length of the square steel pipe in the impact crushing is 100 mm, but in the model using solid elements, the length of the square steel pipe in the FEM model is set to 10 mm to reduce the number of elements due to the need to improve the efficiency of calculation time, and the load in the FEM analysis multiplied by 10 to display it as the press load F. The side length of one solid element is about 0.5 mm, and the total number of solid elements is 48,447. At press loads F=60 to 40 kN, the V-shaped tool and the concave die are in good contact with the square steel pipe plate, and the shape of the side plate is frozen after springback when the load is released (Figure 9(b)), and the inclination angle γ≒0°. In contrast, at a press load of F=25 kN, the V-shaped tool and the concave die do not come into sufficient contact with the square steel pipe plate, but the inclination angle γ of the side plate shape after the springback when the load is released (Figure 9(c)) is γ≒ 1.5° and the protrusion height is about 3 mm based on the center of the plate thickness, so the press load F can be determined to be appropriately set as 25 kN.

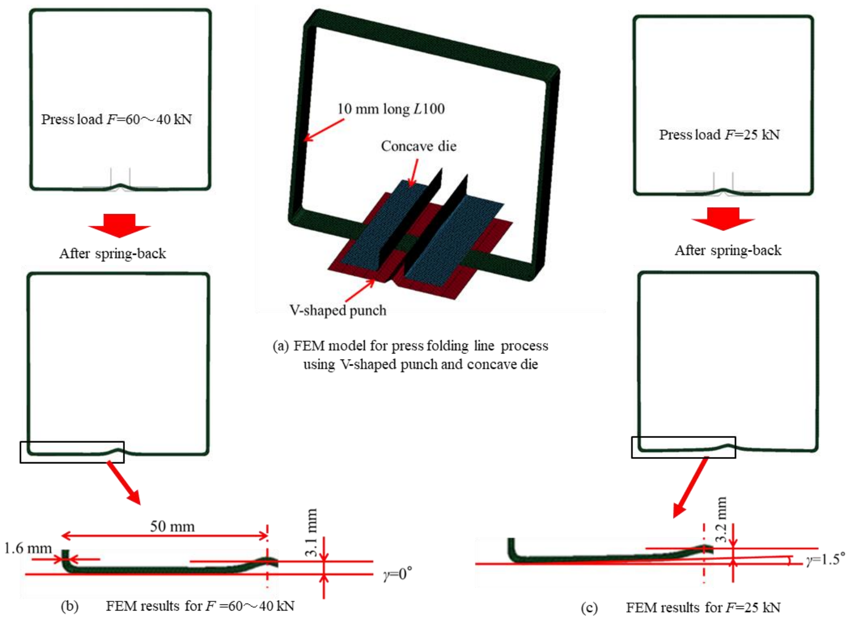


Figure 9. *FEM analysis model for evaluating the appropriate press load for the press folding line process and the deformed shape of the side plate in the cross section of square steel pipe after springback based on FEM results.*

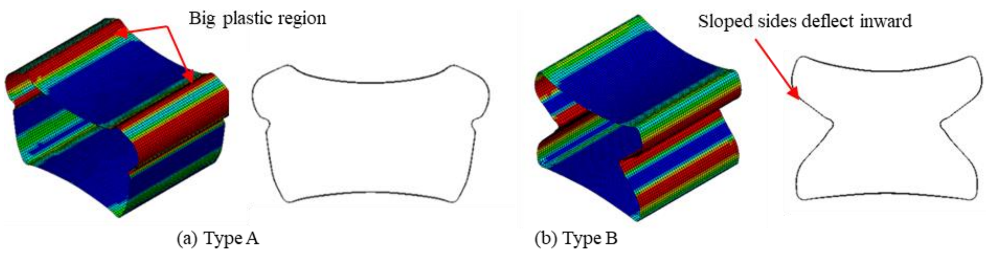


Figure 10. *Equivalent plastic strain distribution and deformed cross section shape at a stage near the die displacement δ =20 mm as V=10m/s..*

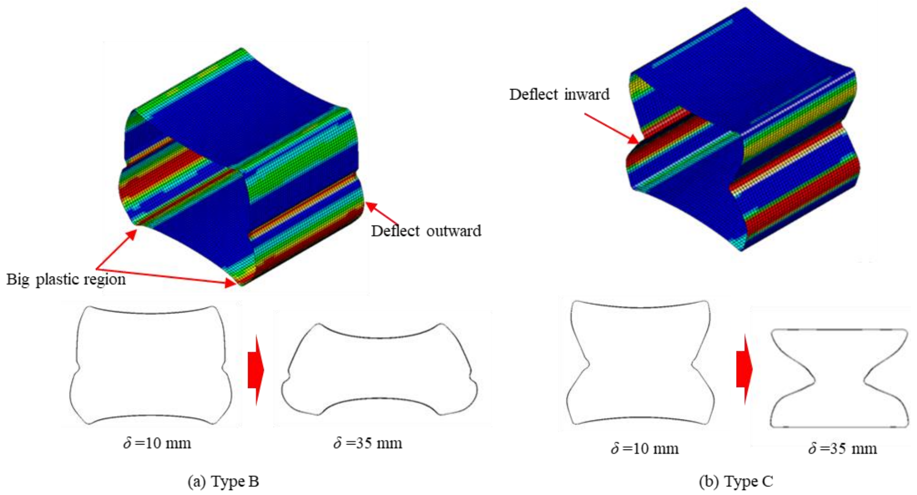


Figure 11. *Equivalent plastic strain distribution and deformed cross section shape at a stage near the die displacement δ =10, 35 mm as V=5 m/s.*

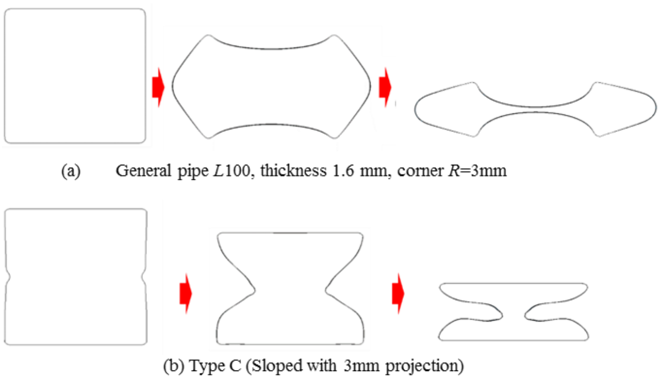


Figure 12. *Comparison between deformation behavior of general pipe during δ=0~60 mm at V=5 m/s and that of Type C based on FEM results.*

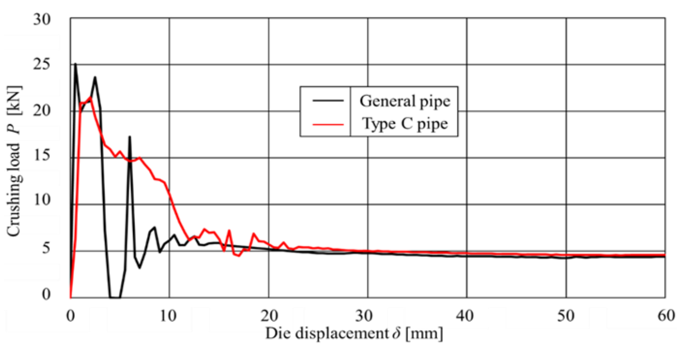


Figure 13. *Comparison between crushing deformation performance of general pipe at V=5 m/s and that of Type C based on FEM results.*

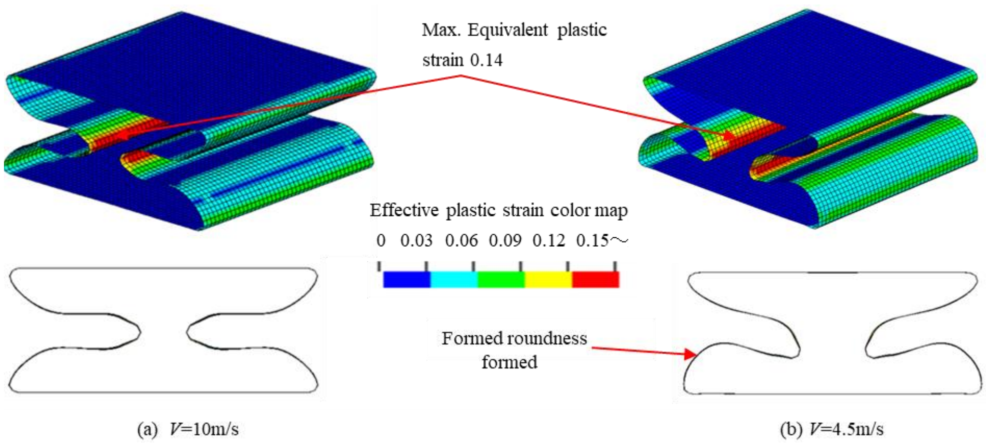


Figure 14. *Equivalent plastic strain distribution and deformed cross section shape at a stage near the die displacement δ =60 mm as V=10 m/s and 4.5 m/s.*

Table 2. *Critical speed V_c [m/s] for 3 types based on FEM results.*

Type	Critical speed V_c m/s
A	NG
B	6.7
C	4.5

Next, using the FEM models of types A, B, and C, FEM analysis is performed under many analysis conditions in which the die speed V is changed in the same manner as in the previous section, with a maximum speed of 10 m/s, to determine the critical speed V_c, and the results are shown in Table 2. Type C has the lowest V_c=4.5 m/s, at which the side plates deform inward being folded compactly.

Examples of FEM results are shown in Figures 10 and 11. Figure 10 shows a comparison of the equivalent plastic strain distribution and cross section deformation shape near the die displacement δ=20 mm for types A and B at V=10 m/s.

The color map is the same as in Figure 6. Since type A does not have a slope on the side plate, the upper corners come into stronger contact with the load die than type B, which has a slope on the side plate, and the plastic region expands significantly, and the corners deform in a direction that widens the angle (the side plates deform outward). Since type B has a slope on the side plate, the side plates are deformed inward being folded compactly. Figure 11 compares the equivalent plastic strain distribution and the cross section deformation shape transition near the die displacement δ = 10 mm for types B and C at V = 5 m/s. The color map is the same as in Figure 6. Both types have a slope on the side plate, but type B has a corner R that is 2 mm larger than type C. The tip of the protrusion at the center of the side plate height direction is approximately 2 mm outside the start position of the corner R. Therefore, when the die speed V decreases from 10 m/s to 5 m/s, the plastic region of the upper and lower corners in Figure 11(a) becomes larger (especially on the lower side plate), unlike Figure 10(b), and the upper and lower corners deform in a direction that widens the angle (the side plates deform outward) as type A in Figure 10(a). In type C, the tip of the protrusion at the center of the side plate height direction is not located outside the starting position of the corner R, so even when the speed drops to V = 5 m/s, the side plates are deformed inward being folded compactly, as shown in Figure 11(b). The critical speed for type C is V_c = 4.5 m/s (Table 2), and the side plates are deformed inward being folded compactly over a wider range of deformation speeds than type B.

As described above, FEM results here are consistent with the speculation made above regarding the effects of die speed and cross section shape on the laterally crushing deformation pattern with corner R.

Next, the deformation behavior and load-displacement transition graphs of a general square steel pipe L100 (plate thickness 1.6 mm, length 100 mm, corner R = 3 mm) and type C at a processing speed V = 5 m/s up to a die displacement δ = 60 mm by FEM analysis are shown in Figures 12 and 13. As the die displacement progresses further, a phenomenon similar to forging occurs, so this paper focuses on crushing deformation up to a die displacement of 60 mm. In the case of a general square steel pipe, the side surface deforms convexly outward, so there are sharp ups and downs after the initial maximum load, but in the case of type C proposed in this paper, the load decreases gradually because the plate material is folded so that it overlaps. The average load of a general square steel pipe is 5.64 kN, and the impact energy absorption is 338 J (= 5.64 kN × 60 mm), while the average load of type C is 6.82 kN, and the impact energy absorption is 410 J (= 6.82 kN × 60 mm), which is an improvement of about 20% in impact energy absorption.

Figure 14 shows the equivalent plastic strain distribution and cross section deformation shape of type C as die displacement δ = 60 mm for the speed range V = 10 m/s and 4.5 m/s, where the side plate of type C deforms inward. The characteristic of the cross section deformation shape at die displacement δ = 60 mm is that at the fast speed V = 10 m/s, only a small roundness is formed at the bottom of the cross section, whereas at the slow speed V = 4.5 m/s, a raised roundness is formed at the bottom of cross section. Although there are such differences in the deformed shapes, the maximum equivalent plastic strain is 0.14 for both, which is the same, and therefore the target value of 0.15 or less of deformation strain due to impact crushing is met in the range of V = 4.5 to 10 m/s.

2.3. Creating Opening by Laterally Impact Crushing

Before conducting experiments on the creating opening of the square steel pipe L100 by laterally impact crushing, the appropriate opening dimension conditions should be examined by FEM analysis. Considering the processing length of the opening shown in Figure 3, in order to make T-shaped square steel pipes L100 (or to avoid interference), about 104 mm is required, taking into account the 2 mm margin on both sides of the 100 mm cross section side length of both square steel pipes. The slit process methods include end mills, side cutters, laser cutting, and wire cutting, each of which has its own advantages, but the most versatile end mill is used. The cut width with the end mill is set to 3 mm, and the crushed part length is set to 98 mm (= 104 mm －2 × 3 mm). The opening depth is set to 50 to 55 mm (crushed part depth 50 to 45 mm) because two crushed parts are overlapped as shown in Figure 3 (a) to make the cross section side length total 100 mm, and the shortfall in dimensions when overlapping is adjusted by setting some shim plates. As shown in Figure 3 (b), a piping diameter of up to 50 mm can be passed through to avoid interference. Next, two same slits are required to impact crush square steel pipes for creating the opening depth of 50-55 mm. Three slit depth plans, 70, 80, and 90 mm, are presented and selected by FEM analysis. Figure 15 shows the FEM model for preliminary consideration. The cross section shape before laterally crushing is based on type C, and while actual square steel pipes have lengths measured in meters, for the experiment and FEM analysis, a short, easy-to-handle square steel pipe length of 200 mm is used. The pipe portion outside the 104 mm range of crushed part is an FEM model of a general square steel pipe shape (Figure 15), with no inclination or protrusions on the side plates. Therefore, as the slit depth becomes shallower, the effect of restraint by the non-inclined side plates becomes stronger, preventing the side plates from being folded compactly. When FEM analysis is performed on the three slit depth plan (70, 80, 90 mm), as shown in Figure 16, for the shallowest depth of 70 mm, the side plates deform outward even at the die speed of V = 10 m/s. This means that the 70 mm slit depth plan is unsuitable, and since the 80 mm slit depth plan should be superior to the 90 mm slit depth in terms of structural strength, it ca be decided to conduct the crushing experiment with the 80 mm slit depth plan.

The conditions as examining the process method proposed in this paper can be set as above.

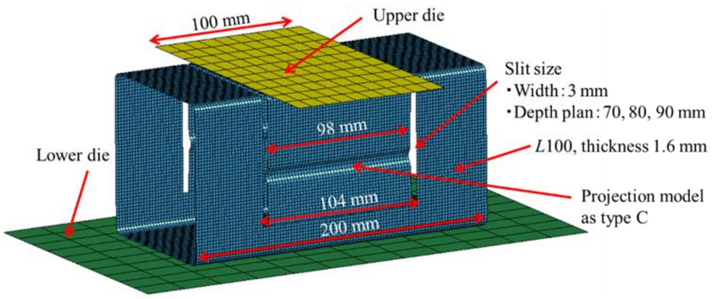


Figure 15. *FEM model for producing opening in L100 pipe by laterally crushing method.*

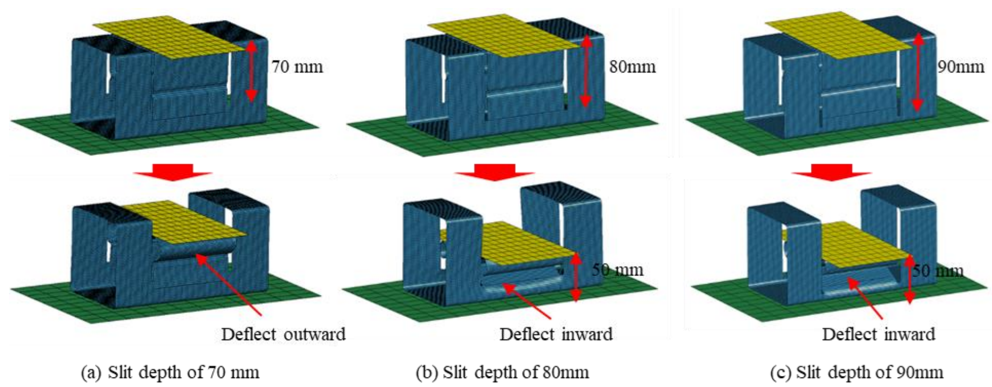
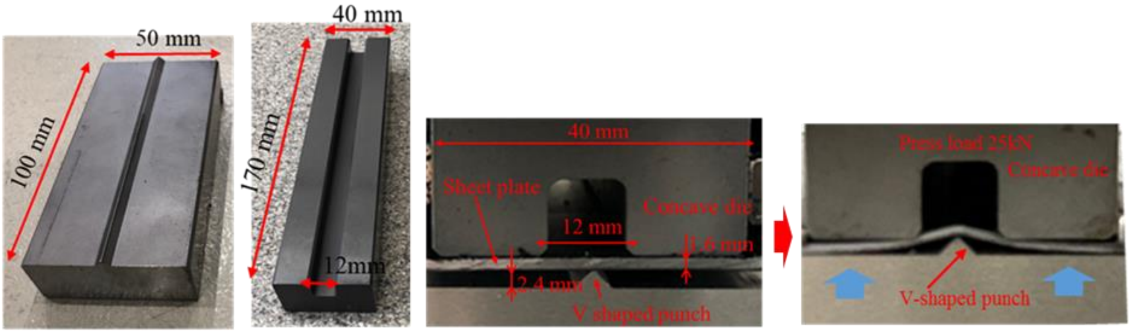
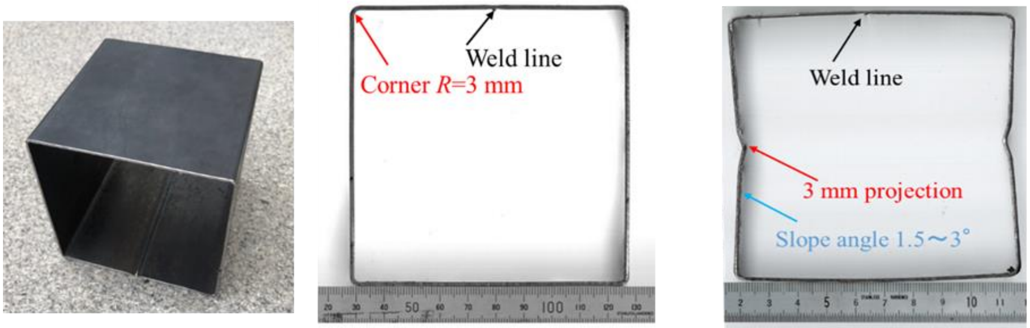


Figure 16. *FEM results for the side plate deformation by V=10 m/s crushing process on three plans as the slit depth of 70, 80, and 90 mm.*



(a) V-shaped punch (b) Concave die (c) Before pressing (d) 25 kN pressing

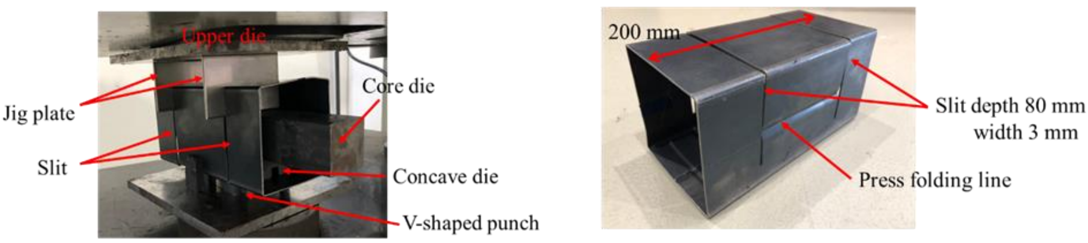
Figure 17. *V-shaped punch, Concave die required for press folding line process and photos of material deformation during processing.*



(a) 100 mm long general pipe (b) General pipe cross section (c) Type C cross section (Sloped with 3mm projection)

Figure 18. *Cross section shape of square steel pipe L100 with a thickness of 1.6 mm.*

(a) Square steel pipe *L*100 with a length of 200 mm setting in the machining center (b) Pipe with cut-off



(c) Press folding line processing for pipe with two slits (d) Pipe with two slits and press folding lines

Figure 19. *Experimental member fabrication for 200 mm long square steel pipe L100 with cut-off and press folding lines. MC processing machine to perform cut-off and slit processing. For the press folding line process, two 3 mm thick jig plates inserted into two slits transmitting a load of 25 kN to the pipe.*

3. Experimental Results and Discussion

3.1. Trial Press Folding Line Process for Square Steel Pipes as Experimental Members

Based on the die set specifications for the press folding line process discussed in the previous chapter, the die set should be produced. This set consists of a V-shaped tool and a concave die, which are cut from commercially available SKD11 steel blocks using an MC processing machine and heat treated. A press load of 25 kN is applied to the side plate of a square steel pipe *L*100 (plate thickness 1.6 mm, corner R = 3 mm) as the folding line process (Figure 17). Figure 17(d) shows the application of the press load corresponds to FEM results (Figure 9(b)). Figure 18 shows a cross section photograph of the square steel pipe. According to JIS G3466: 2021 [1], the dimensional accuracy of the square steel pipe *L*100 is within ±1.5 mm in side length error and ±0.3 mm in plate thickness error. As can be seen from the cross section photograph (Figure 18), there is a dimensional error in commercially available square steel pipes due to the influence of the shape dimensions of the weld line, and there is a distribution in the side length and plate thickness. Therefore, the plate thickness reduction by press folding line process is within the range of the dimensional accuracy of the square steel pipe and is at a negligible level (Figure 18(b), (c)).

The cross section of the square steel pipe produced by the press folding line process (Figure 18(c)) has a side plate shape with an inclination angle of γ = 1.5 to 3°, as targeted in the previous chapter, and a protrusion height of approximately 3 mm based on the center of the plate thickness.

Note that care should be done to ensure that the plate with the weld line be not the target plate for the press folding line process.

Next, to produce the experimental members of 200 mm long square steel pipes (Figure 19), an end mill is set on the MC processing machine to perform notching and slitting. For the press folding line process, two 3 mm thick jig plates are inserted into the two slits, and a press load of 25 kN is transmitted to the concave die via the core die.

3.2. Laterally Impact Crushing Square Steel Pipes

FEM results (Figures 12, 13) for *L*100 square steel pipe in the previous chapter show that the type C square steel pipe with a 3 mm convex protrusion on the side plate formed by press folding line process has better impact energy absorption performance at a die speed of 5 m/s than that of a general square steel pipe. This effect is verified experimentally (three experiments each) using a high-speed impact testing machine (Tokyo Koki Co., Ltd., model number TPLz100XQ400, maximum load 400 kN, maximum die speed 10 m/s). Note that this testing machine is a hydraulic machine, so impact crushing experiments under constant die speed control as in the FEM analysis conditions, cannot be performed. As explained in the previous report [14, 16], the die speed setting is the target die speed, and speed changes due to acceleration and deceleration occur around the target die speed. Figure 20 shows characteristic photos of the deformation behavior of two experimental members in laterally impact crushing experiments taken with a high-speed camera.

In the case of a general square steel pipe, large deformation occurs inward on both the top and bottom plate, and the crushing deformation progresses so that both side plates spread outward. In contrast, for type C square steel pipe, the 3 mm protrusions provided in the center of both side plates induce deformation inward, being folded compactly, and the deformation of the top and bottom plate is small, and their crushing deformation progresses in a state close to flat.

Next, Figure 21 shows load-die displacement transition graphs for impact crushing experiments conducted three times for both members, output from the impact testing machine every 0.1 ms. It is clear that the load transition of a general pipe has more drastic ups and downs than that of type C, but the graphs for both members have large ups and downs due to the effects of vibration during the test, making it difficult to compare them. Therefore, Figures 22, 23 show graphs comparing the average load and average die speed calculated for each 10 mm of die displacement for the results of the impact crushing experiments conducted three times for both members. As this is a hydraulic testing machine, there is some variation between the two in the average speed transitions for every 10 mm of die displacement (Figure 23), but the average die speed up to 40 mm of die displacement is approximately the same for both, at approximately 5.3 m/s, and it rapidly decelerated after 40 mm of die displacement, and both stopped after 60 mm of die displacement. The die speed decreases in the latter half, but as can be seen from the deformation behavior of the side plates of the square steel pipe in Figure 20, the side plates have already deformed inward being folded compactly, so even the speed decreasing, it never starts to deform outward.

The average load for a general square steel pipe is 5.0 kN and the impact energy absorption is 300 J up to a die displacement of 60 mm, while the average load for a type C square steel pipe is 6.0 kN and the impact energy absorption is 360 J. The die speed V in the experiment is different from the constant V = 5 m/s, which is the FEM analysis condition, but FEM results (Figures 12, 13) for the average load and impact energy absorption of both square steel pipes are about 10% off the experimental results. It is experimentally verified that up to a die displacement of 60 mm, when the side plates are inward folded compactly so that they overlap, impact energy absorption is improved by about 20% compared to a general square steel pipe, which the side plates deform outward so that they spread out.

As described above, when type C square steel pipes are used for guardrails and the like, even if they are crushed by impact in an accident, they will be folded compactly within their cross section, causing no harm to the surrounding area, and because they have high impact energy absorption performance, improved safety will be expected.

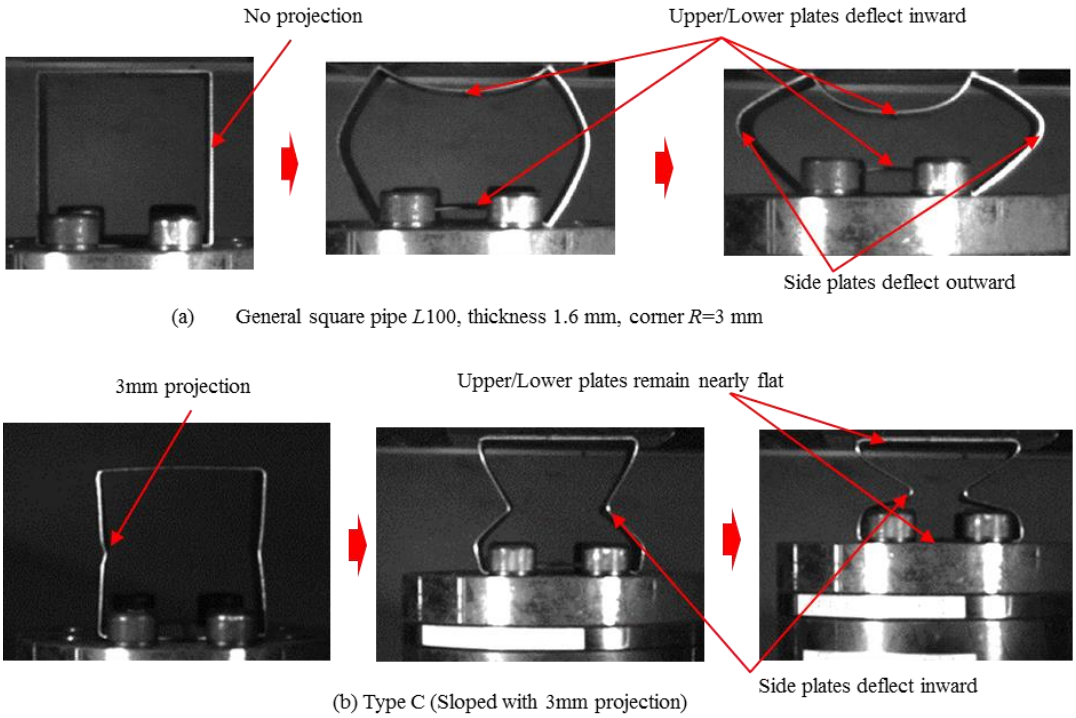


Figure 20. *High-speed camera images of crushed square pipe cross section deformation behavior at die speed of about 5 m/s.*

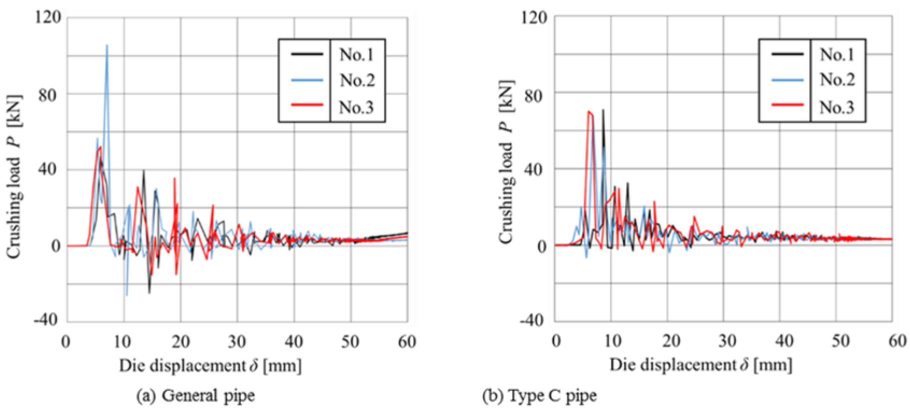


Figure 21. *Comparison of No.1-3 measured data of crushing load-die displacement transition between the general pipe and the type C pipe in 5 m/s die speed case.*

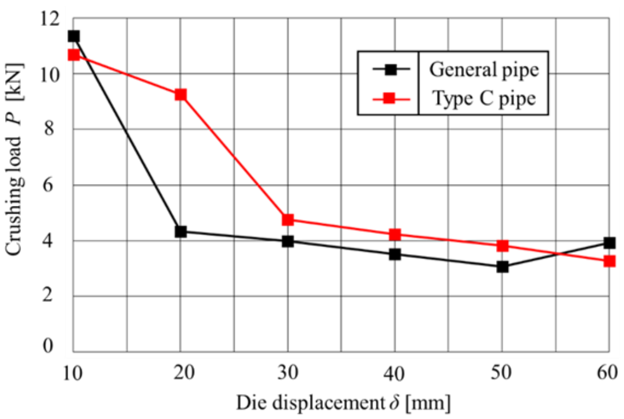


Figure 22. *Comparison of measured data of crushing load-die displacement transition between the general pipe and the type C pipe in the average transition for each 10 mm die displacement for No.1-3 experiments.*

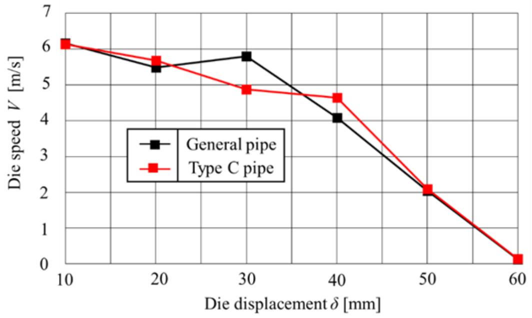


Figure 23. *Comparison of measured data of die speed vs. die displacement transition between the general pipe and the type C pipe in the average transition for each 10 mm die displacement for No.1-3 experiments.*

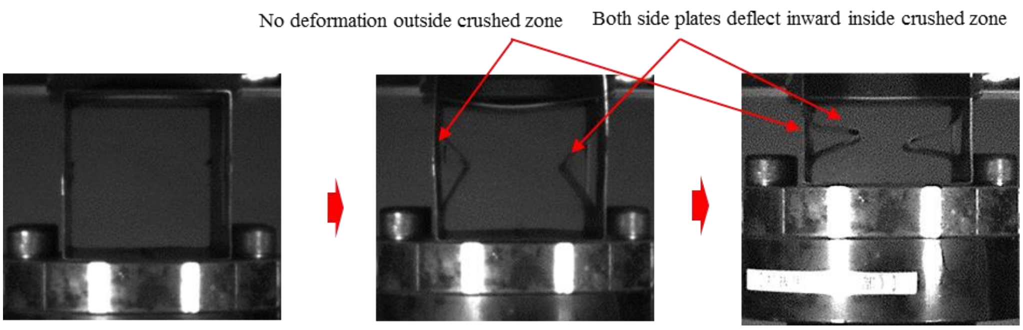


Figure 24. *High-speed images of crushed square pipe cross section deformation behavior at a die speed of about 10 m/s. These photos show no deformation outside the crushed zone and both side plates deflected inward inside the crushed zone.*

3.3. Trial Production of Square Steel Pipes with Crushed Part

Using 200 mm long experimental members as described in the previous section, the verification that a square steel pipe with an opening can be produced by laterally impact crushing process at a die speed of 10 m/s, as shown in FEM results (Figure 16), is carried out by experiments. Figure 24 shows characteristic photographs taken with a high-speed camera of the deformation behavior of experimental members in laterally impact crushing process. The photographs show that the inner area between two slits setting 104 mm apart, each slit width of 3 mm, is laterally crushed, while the outer area is in the normal square steel pipe state. Figure 25 shows photographs of the trail produced members. The photograph of the cross section shape of member is shown in Figure 25(c), which represents that the crushed area meets the target depth of 45 to 50 mm, and that breaks or significant reduction in plate thickness have never occurred due to impact crushing process. However, there is a concern that even if the impact crushed part remains, it may be too weak to expect any reinforcing effect, so the following strength tests are carried out. Strength tests are conducted for three members (Figure 26: a general pipe, a general pipe with cut-off, and a general pipe with crushed part) made from square steel pipes *L*100, applying a load using a 100 mm long upper die by a universal testing machine (Tokyo Koki, model TK21) under displacement control (quasi-static die speed 20 mm/min). The load-displacement transition graph and maximum load data are shown in Figure 27 and Table 3.

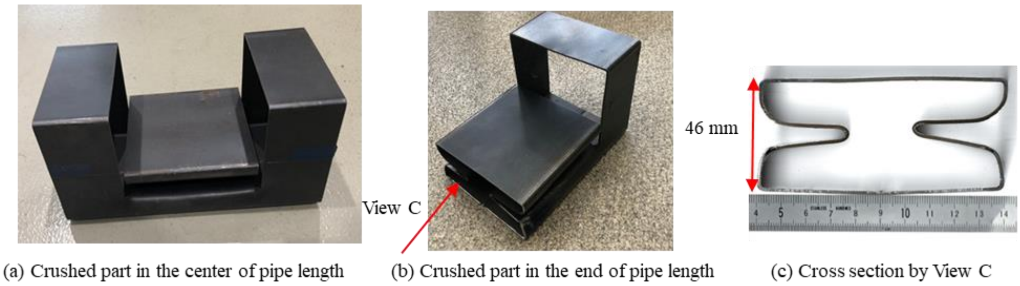


Figure 25. *Photos of products by impact crushing process for square steel pipes to perform the opening. The cross section photo shows that conforming the target depth of the crushed part of 45 to 50 mm, and that no fractures and no large thickness reductions have occurred due to the impact crushing process.*

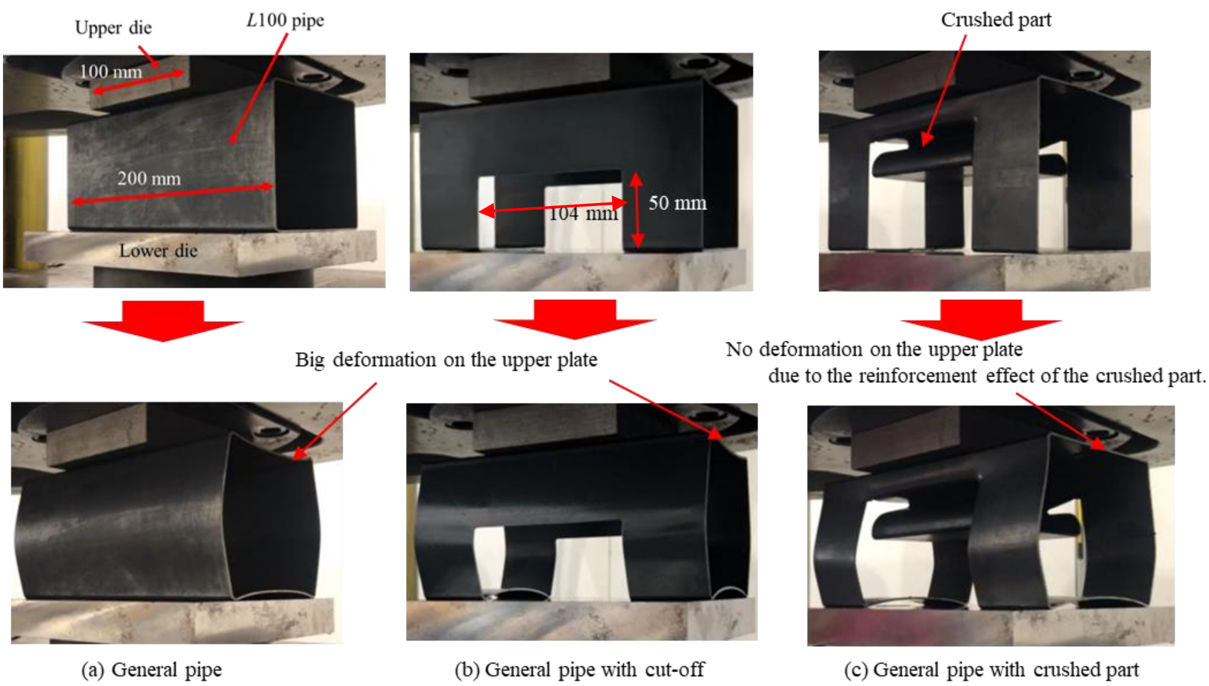


Figure 26. *Three experimental members as length 200 mm general pipe L100, general pipe with cut-off and general pipe with crushed part, setting in the universal testing machine. Strength evaluation experiments are performed using displacement control (quasi-static loading die movement speed 20 mm/min). The upper plate of general pipe and that of cut-off have big deformation. On the other hand, that of crushed part has No deformation. It is observed that crushed part can contribute as reinforce.*

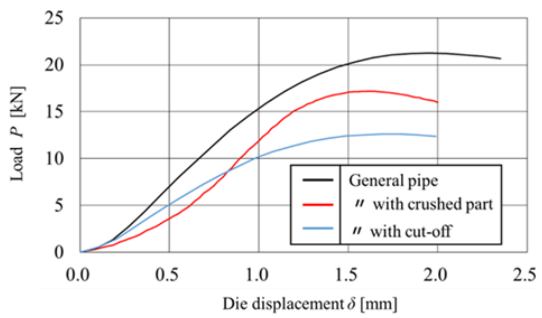


Figure 27. *Comparison of measured data of load-die displacement transition between the general pipe, general pipe with cut-off and general pipe with crushed part at a die speed of 20 mm/min.*

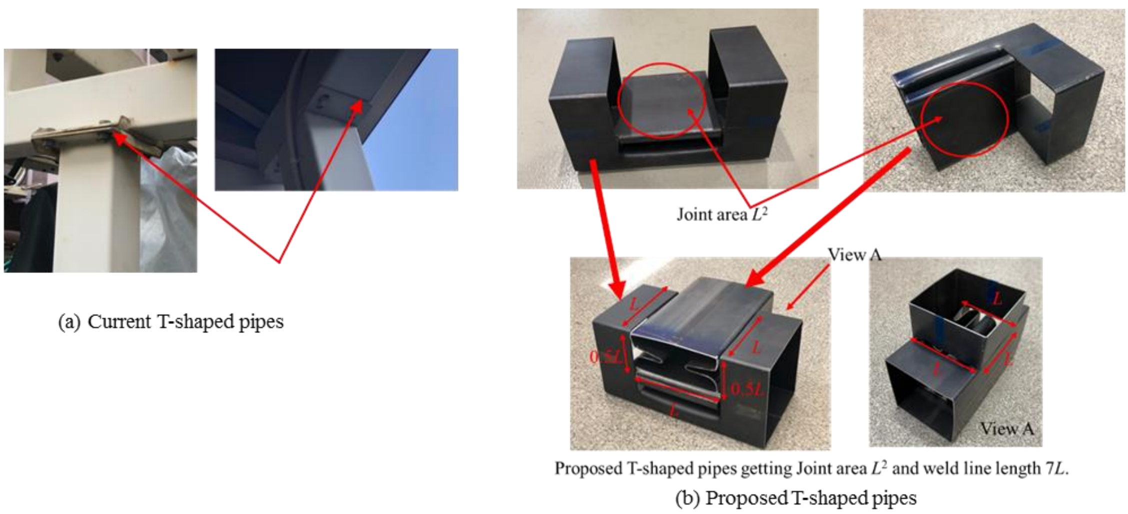


Figure 28. *Applicable T-shaped pipes. Reinforcing materials such as flange plates are often used on current T-shaped pipes.*

Table 3. *Maximum load data from strength tests.*

Member	Maximum load kN
General pipe	21.3
General pipe with cut-off	12.6
General pipe with crushed part	17.2

The following findings are obtained from the strength test results.

(1) The maximum load for a general pipe member is 21.3 kN, while that for a general pipe member with cut-off is 12.6 kN, which is approximately 60% of a general pipe member.

(2) The maximum load for a general pipe member with crushed part is 17.2 kN, which is approximately 80% of a general pipe member. So, reinforcing effect can be seen when compared to a general pipe member with cut-off.

(3) When a load is applied to both a general pipe member and that with cut-off, the upper plate is greatly dented and deformed, but in the general pipe member with crushed part, the upper plate is hardly deformed due to the reinforcing effect of crushed part. This strength test confirms that the crushed part that remains after the impact crushing is not weak but strong.

(4) The loading conditions differ depending on the application, so it is difficult to make a general statement, and in order to mass-produce it as an actual part, there are many development issues such as measures to deal with the effects of the geometry and dimensional tolerance of square steel pipes (initial irregularities in dimensions, angles, etc.). However, when a square steel pipe member with crushed part can be developed for practical use using the process method proposed in this paper, it may be possible to use it as a square steel pipe structural member with an opening without adding reinforcement. Applicable areas are openings and intersections in steel pipe structures. As shown in Figure 28(a), reinforcement such as flange plates is often used at the current T-shaped steel pipe intersections. This is probably because the current product as T-shaped steel pipe has a weld line length of only $4L$ (meaning $4\times L$, the same below) around a joint plate, and so a reinforcing material such as a flange plate is required to make it easier to join. In contrast, when a pipe member with crushed part is used as shown in Figure 28(b), adhesives or bolt fastening can be used on the contact area (the cross section side length L^2) and the total weld line length increased as $7L$, making it easier to join without using reinforcing materials. In addition, if a square pipe with crushed part is used in a joint location such as that shown in Figure 29, rather than being limited to a T-shape, the remaining crushed part acts as a reinforcing part, and the joint contact area and total weld length increased, making it easier to join. It can be called a smart intersection.

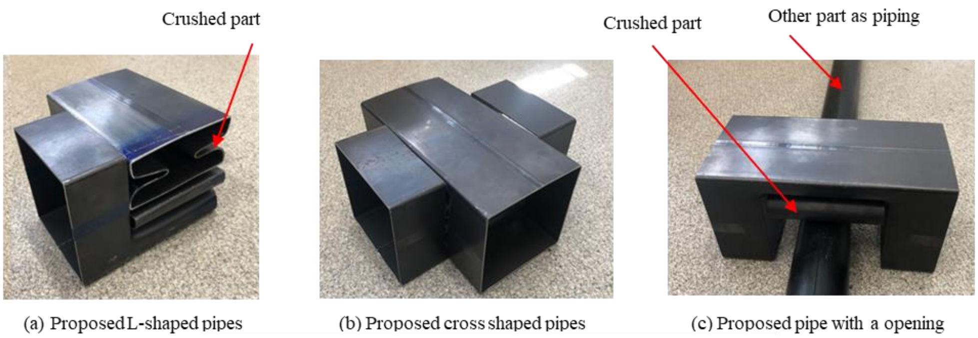


Figure 29. *Applicable structures as pipe intersections and opening.*

Finally, there are the following precautions to take when implementing the proposed process method.

1) Use of support jigs for keeping the position of square steel pipes in the press folding line process: As shown in Figures 17 and 19(c), support jigs are required to stabilize the position of square steel pipe in the press folding line process. When these support jigs are installed, the square steel pipes cannot be seen and the procedure cannot be explained, so support jigs were removed at the case of photographing Figures 17 and 19(c).

2) Use of core jigs for keeping square steel pipes shape in the impact crushing process: As shown in Figure 24, when impact crushing only the inside between two slits in a square steel pipe, it is better to install core jigs to maintain the shape of the square steel pipe as the outside between two slits. When these core jigs are installed, it is not possible to photograph the deformation behavior inside between two slits, so core jigs are not used at the case of photographing Figure 24.

3) Deformation defects due to weld lines of square steel

pipes: Square steel pipes have weld lines, and depending on the production lot, there can be deformation defects occasionally in which the weld lines are significantly bent during the cross section deformation in the laterally impact crushing process, as shown in Figure 30. In this paper, elucidating the mechanism of such deformation defects in weld lines is outside the scope of the research.

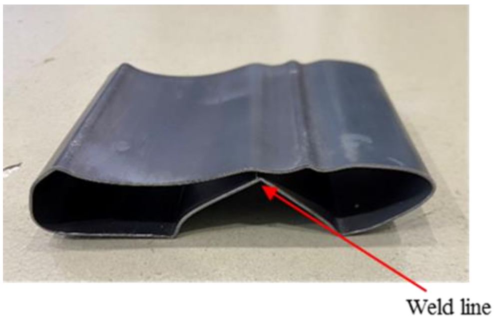


Figure 30. *Deformation defects occasionally occurring at the weld line in laterally impact crushing experiments.*

4. Conclusions

The conclusions of this report are as follows:

1. For virtual steel square steel pipes (plate thickness 1.6 mm, cross section side length L50, 100, 150, 200) with no rounded corner, FEM analyses are performed to investigate the deformation behavior of cross section shape in laterally impact crushing process with changing the die speed as analysis conditions, in a maximum speed range of 10 m/s. FEM results show that the critical speed must be exceeded in order to fold the side plates compactly. When the die speed is faster than the critical speed, the side plates are folded compactly, and when it is less than the critical speed, the side plates deform outward. Under these conditions, an approximate relationship could be observed in which the critical speed is inversely proportional to the cross section side length L2.
2. In this paper, FEM models for actual square steel pipes L100, 100 mm long, plate thickness 1.6 mm, corner R = 3, 5 mm with some side plate shape conditions are presented. Conducting numerous FEM analyses to investigate the cross section shape conditions and die speed conditions that result in a deformation pattern in which the side plates are folded compactly, the following findings are obtained.
   a) In the case of actual square steel pipes, the critical speed should be needed, and the higher the die speed, the easier the side plates be folded compactly as same as the case of virtual square steel pipes with corner R = 0.
   b) Comparing FEM results for cases, the cross section side plate is vertical, the side plate is inclined inward, and corner R = 3, 5 mm, etc., the findings are obtained. When the side plate is vertical and does not inwardly incline, even with a protrusion in the center of the side height direction, and even the die speed be further increased, the side plates definitely deform outward in the laterally crushing process. When there is a corner R, it is a necessary condition that the side plates should be inwardly inclined, and the further the tip of the protrusion in the center of the side plate is located inside the corner R start position, the easier the side plates deform inward being folded compactly in laterally crushing process. On the other hand, when it is not located inside the corner R start position, a higher die speed is required to fold side plates compactly.
   c) Processing conditions are presented to make the side plate appropriate inclined by press folding line process as forming a protrusion in the center of the side plate height direction. FEM results based on these conditions show that when the side plate deforms inward being folded compactly at a die speed of 5 m/s, the impact energy absorption that the cross section height of 100 mm is impact crushed to 40 mm, is approximately 20% higher than that of a general square steel pipe which the side plates deform outward.
   d) FEM models of square steel pipes with two slits are created. Two slits are setting 104 mm apart. Each slit wide 3 mm and three depth plans are 70, 80, 90 mm in a square steel pipe with a length of 200 mm. Conducting FEM analyses to select the slit depth plan that create an opening as 104 mm long, 50 mm depth by laterally impact crushing between two slits at a die speed of 10 m/s. A deeper slit reduces resistance and makes it easier for the side plate to be folded compactly, but the structural strength is reduced, so the slit depth needs to be shallow. At a slit depth 70 mm, the side plates deform outward even at a die speed of 10 m/s, and at slit depth 80 and 90 mm, the side plates can be folded compactly, so 80 mm depth plan is selected.
3. The die set for a press folding line process can be produced in order to form the target cross section shape based on FEM results. Using this die set, the press folding line process is performed under the specified processing conditions. Experimental members with the target cross section shape are produced using commercially available square steel pipes (L100, plate thickness 1.6 mm, corner R = 3 mm) with a length of 100 mm and laterally impact crushing experiments are conducted. The deformation behavior of cross section shape in laterally impact crushing experiments, in which the cross section height of 100 mm is reduced to 40 mm at a die speed of approximately 5 m/s, can be

photographed with a high-speed camera. The protruding fold line provided in the center of the inclined side plate functions as a deformation inducer, and the side plates are inward folded compactly, which is approximately 20% more effective than the impact energy absorption of a general square steel pipe, in which the side plates are deformed outward. This compactly folding deformation pattern is safe and does not pose a risk to the surroundings. It is expected to be used in structural members such as guardrails.

4. Two slits, 3 mm wide and 80 mm deep, spaced 104 mm apart, are machined in a 200 mm long square steel pipe with an end mill and an opening, 104 mm long and 50 mm depth, can be produced by impact crushing the area between two slits. This square steel pipe with crushed part is strong without any reduction in plate thickness that cause breakage or risk of breakage, and strength tests show that crushed part functions as a reinforcing member.
5. In this paper, the verification that square steel pipes with crushed part can be prototyped as steel structures by using commercially available square steel pipes (L100, plate thickness 1.6 mm, corner R = 3 mm) and conducting preliminary FEM analysis, is performed experimentally. But the application limits (steel type, dimensions, etc.) are not studied. However, when the process method proposed in this paper will be applied to develop square steel pipe members with crushed part to create openings in steel structures, not only will it be possible to avoid interference without adding additional reinforcement materials, but it is expected to have the advantage of making it easier to join L-shaped, T-shaped, and cross-shaped intersections.

Abbreviations

L	Cross Section Side Length of Square Steel Pipe
R	Roundness is Referred to as Radius *R*

Author Contributions

Kosuke Terada is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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Research Fields

Kosuke Terada: Mechanical Engineering