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ORIGINAL ARTICLE

Flexible-bending of profiles with asymmetric cross-section and elimination of side bending defect

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Abstract Flexible-bending is a relatively novel bending process, particularly suitable for profile and tube bending. Advantageous characteristics, such as manufacturing profiles or tubes of different radii without die change and continuous forming of bent profiles or tubes, make flexible-bending highly applicable and efficient especially in small batch production. In this paper, flexible-bending process of angle iron which is a typical asymmetric-section profile was investigated with finite element analysis method. The effect of die offset on radius of bent angle iron in outward and inward bending process was investigated. The cause and elimination method of side bending defect in bent angle irons were analyzed and compared with the experimental results. The simulation results agree well with the experimental results, which verify the feasibility of using simulation to guide the experiment. The results of both simulations and experiments indicate that the curvature of bending angle iron and side bending increases linearly with the die offset. The curvature of side bending outward is larger than the curvature of side bending inward of same die offset. The side bending defect can be eliminated by shifting the die in reverse direction of side bending.

Keywords Flexible-bending · Profile · Angle iron · Die offset · Side bending · Curvature

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1 Introduction

The demand of bent profiles in different industrial sectors increases because of lightweight design, space, and cost saving [1]. Especially, lightweight design of the components plays a more and more important role for economic and ecological reasons [2, 3]. Profiles are widely used in automobiles, shipbuilding, and aerospace industry, where bent profiles with various cross-sections are needed [4–6]. This means that the bending process is required not only to bend profiles with circular and simple symmetric cross-sections but also to bend profiles with asymmetric cross-sections [7].

Murata proposed flexible-bending method, the principle of which is adjusting the position of bend die penetrated by tubes or profiles, to bend tubes or profiles of different radii without die change and reclamping [8]. Gantner investigated a so-called free-bending technology to form a free definable bending geometry with transitionless bend-in-bends and spline bends [9], which is based on the same bending principle. At present, studies about flexible-bending are mainly focused on tubes and profiles with rectangular cross-sections [10]; flexible-bending of profiles with asymmetric cross sections is rarely studied.

In the bending process of profiles, defects such as springback and wrinkle are involved [11, 12]. In the case of bending profiles with asymmetric cross-sections like angle irons, side bending defect is particularly obvious and required to be analyzed [13, 14].

In this paper, profiles with asymmetric cross-sections angle irons are used to investigate flexible-bending method. Finite element analysis method is applied to investigate the curvature variation trend and the occurrence and elimination of side bending defect when flexible-bending is applied to form profiles with asymmetric cross-sections, which are compared with experimental results.

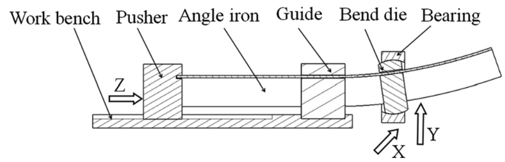

Fig. 1 Schematic diagram of flexible-bending principle

2 Principle of flexible-bending

The schematic diagram of flexible-bending principle is shown in Fig. 1. The guide is fixed on workbench and a pusher can move along the *Z* direction. In the process of bending, angle iron is penetrated into the bend die, a bearing drives the bend die to move a distance in the *Y* direction and a pusher feeds the angle iron in the *Z* direction through the guide and the bend die. The movement of the bend die in the plus *Y* direction results in outward bent angle iron, whereas the movement of the bend die in the minus *Y* direction results in inward bent angle iron. Compared with other bending methods such as rotary draw bending where the final forming geometry is defined by the geometry of the bend die [15], the forming geometry of the flexible-bending process is defined by the offset of the bend die. Forming bent angle irons of different radii by adjusting the location of the bend die, flexible-bending of profiles is achieved.

3 Bending tests

Figure 2 shows the computer numerically controlled (CNC) flexible-bending equipment developed by Jilin University. Double-coordinate workbench is driven by two servo motors, which enable the bend die to shift in the *X* and *Y* directions. The feed system driven by a servo motor is composed of the chain wheel and chain link mechanism, which is able to feed the profile in the *Z* direction for long travel.

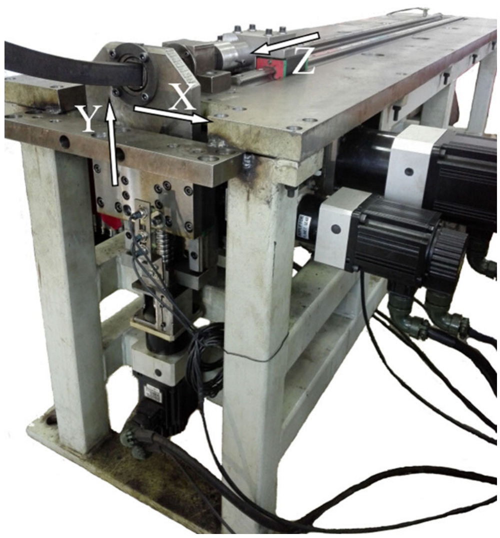

Fig. 2 CNC flexible-bending equipment

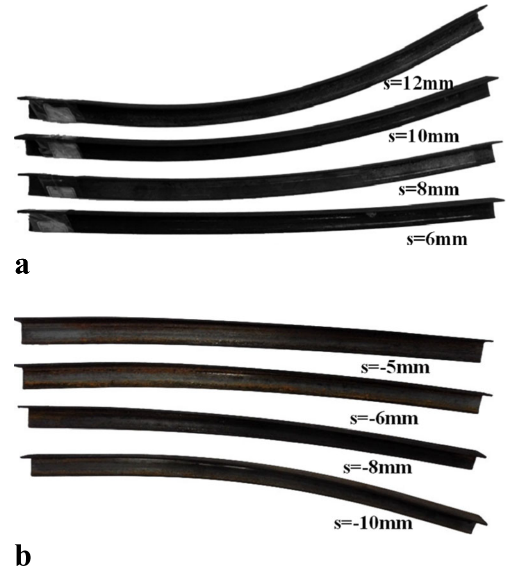

Fig. 3 Experimental results of bent angle irons. **a** Outward bending results. **b** Inward bending results

Flexible-bending tests of angle irons have been carried out in the CNC flexible-bending equipment; the side

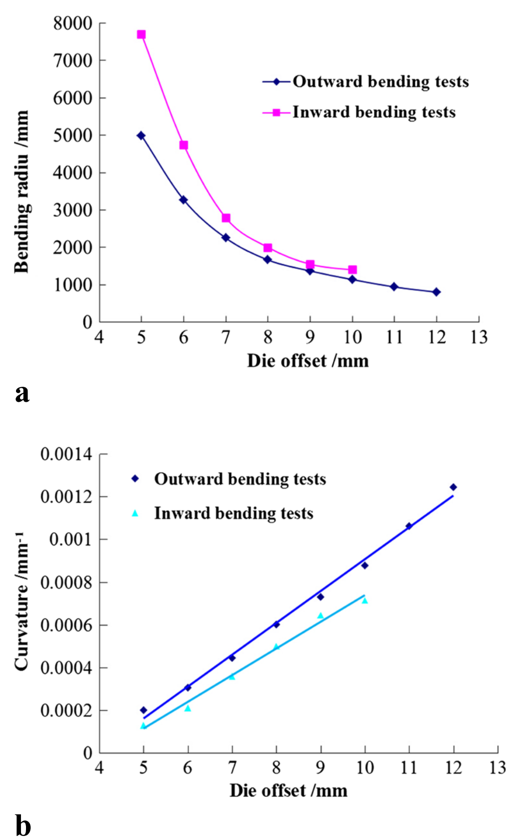

Fig. 4 Results of the radii and curvatures of bent angle irons. **a** Experimental results of bending radii. **b** Experimental results of curvatures

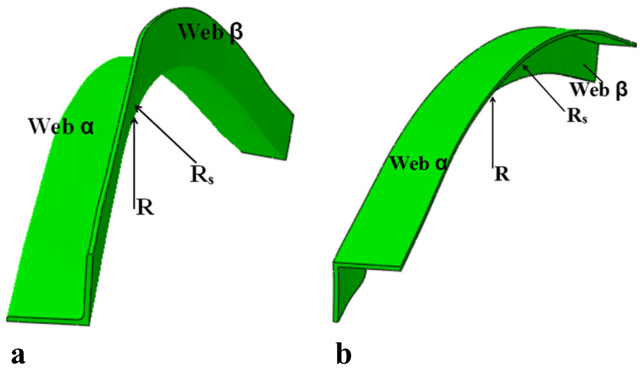

Fig. 5 Schematic diagrams of side bending. **a** Outward bending. **b** Inward bending

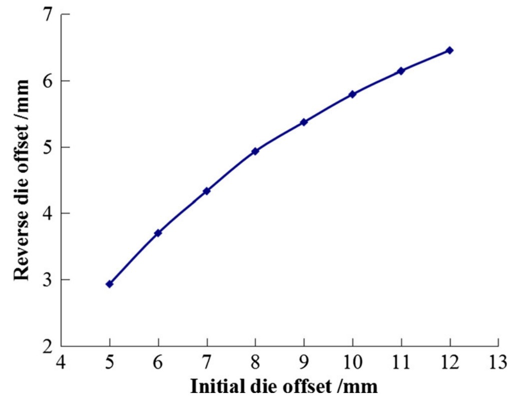

Fig. 7 Reverse die offsets for elimination of side bending defect

bending defect occurring in bent angle irons has been verified. Figure 3 shows the experimental results of bent angle irons of different die offsets. The die offsets in Fig. 3a are in the plus *Y* direction, which from the bottom to top are respectively 6, 8, 10, and 12 mm. The die offsets in Fig. 3b are in the minus *Y* direction, which from top to bottom are respectively −5, −6, −8, and −10 mm. Figure 4 shows the results of the radii and curvatures of bent angle irons. Die offset in the *Y* direction varies from 5 to 12 mm; die offset in the minus *Y* direction varies from −5 to −10 mm, which will result in wrinkle in angle iron when it reaches above −10 mm. From the experimental results, it is observed that the curvatures of bent angel irons increase linearly with die offsets. The outward bending curvature is larger than the inward bending curvature of the same die offset.

Side bending is a typical defect in bending process of profiles with asymmetric cross-section. The schematic diagrams of side bending in bent angle irons are shown in Fig. 5. The bending radius of web α is *R*, and that of web β is R_s, which is the radius of side bending. It can be observed that the directions of side bending in outward bending (as shown in Fig. 5a) and inward bending (as shown in Fig. 5b) are opposite. In the process of flexible-bending of angle iron, the side bending defect can be eliminated by setting die offset in the reverse direction of side bending.

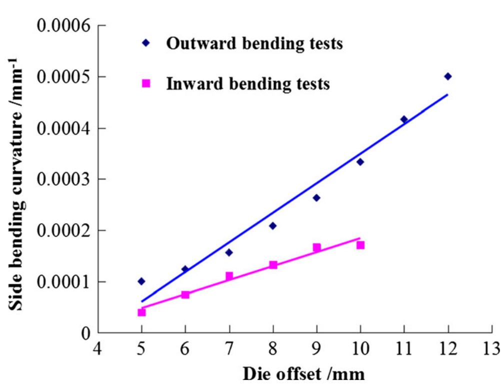

Fig. 6 Experimental results of side bending curvatures

Figure 6 shows the results of side bending curvatures of angle irons of different die offsets. The curvatures of side bending increase linearly with die offsets, and side bending curvature of outward bending is larger than that of inward bending of the same die offset. Figure 7 shows the results of die offsets in reverse direction of side bending for elimination of the defect.

The experimental results of bent angle irons with and without side bending verification by means of reverse die offset are represented in Fig. 8. It shows that the side bending defect is eliminated through verification, which indicates that bent angle irons without side bending defects can be obtained by means of this verification method.

4 Simulation of flexible-bending process

4.1 Finite element analysis model

To research the flexible-bending process of angle iron, ABAQUS/explicit is used to conduct numerical simulation of the forming process. The dimension of the cross-section of angle iron is 28 × 28 × 2 mm, which is the same with experiments. The material of angle iron used in the numerical simulation is Q235; the relevant material parameters are shown in Table 1. Figure 9 shows the finite element model of flexible-bending of angle iron. The angle iron is dispersed into 3450 C3D8R solid elements which is an eight-node linear brick, reduced integration element, and other parts are defined as rigid bodies. The coefficient of friction at contact surfaces between the parts is 0.2.

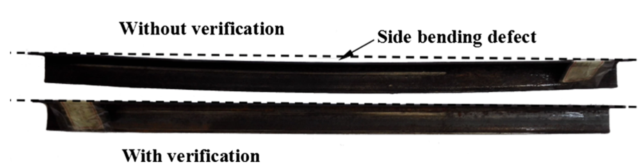

Fig. 8 Bent angle irons with and without side bending verification

Table 1 Material parameters of angle iron

Material	Density	Elastic modulus	Yield strength	Elongation	Poisson's ratio
Q235	7850 kg/m^3	210 Gpa	235 Mpa	25 %	0.285

4.2 Curvature of bent angle iron

The process of flexible-bending of angle iron can be divided into period of bend die offset and period of feeding angle iron. Figure 10 shows the simulated results of forming process. In the period of die offset, the bend die moves a distance in the *Y* direction driven by bearing. In the period of feeding angle iron, the pusher feeds the angle iron in the *Z* direction.

Figure 11 shows the simulation results of the equivalent strain distribution of bent angle irons of different die offsets, where s = die offset (mm). The die offsets in Fig. 11a, b are in the plus *Y* direction, which are respectively 6 and 10 mm. The die offsets in Fig. 11c, d are in the minus Y direction, which are respectively −6 and −10 mm. From the simulated results, it is observed that the strain in the bent angle iron increases as the die offset increases in the plus or minus *Y* direction. Whenever the angle iron is bent outward or inward, the strain occurs mainly on the web perpendicular to the bent web.

Die offset is the main factor to affect the curvature of bent angle iron; the results of the influence of die offset on curvature of bent angle iron are shown in Fig. 12. It is observed that the curvature of bent angle iron increases linearly as the die offset increases and that the curvature of outward bent angle iron is larger than that of inward bent angle iron of the same die offset. Whether the angle iron is bent outward or inward, the bending curvature in experimental results is comparatively smaller than that in simulated results.

Figure 13 shows the stress distribution in the deforming region of angle irons. When angle iron is bent outward (as shown in Fig. 13a), the web perpendicular to the bent web is subjected to tensile stress, which leads to comparatively bending stability. In the case of inward bending (as shown in Fig. 13b), the web is subjected to compressive stress,

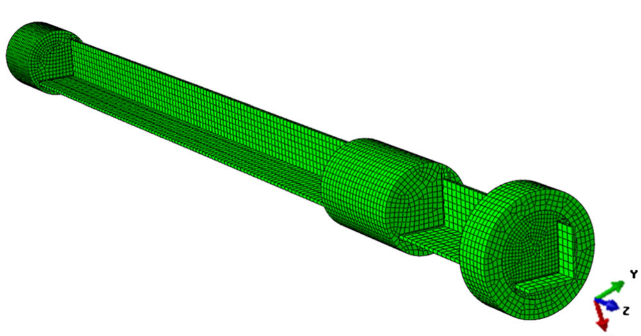

Fig. 9 Finite element model of flexible-bending of angle iron

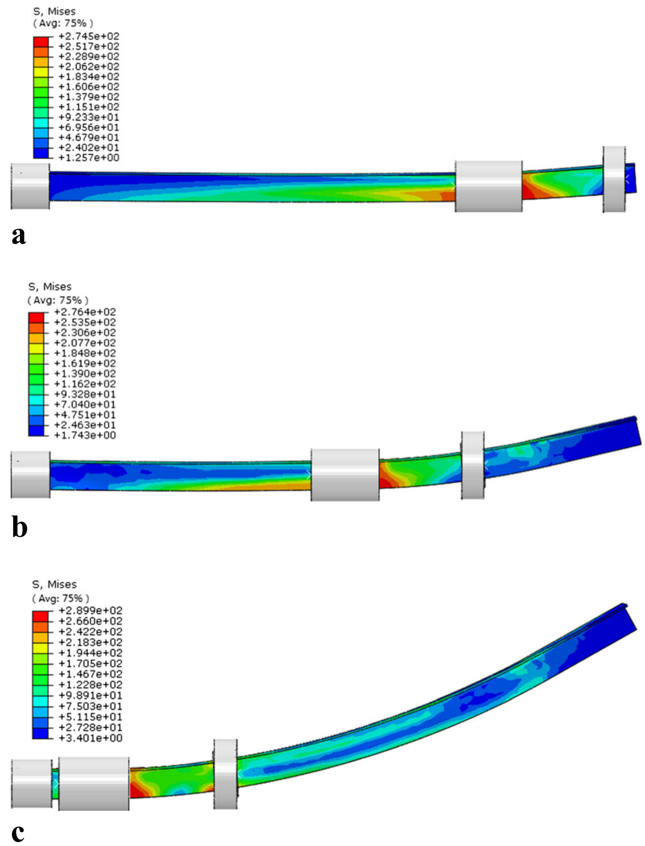

Fig. 10 Simulation results of angle iron forming process. **a** Period of bend die offset. **b** Period of feeding angle iron. **c** Bending completed

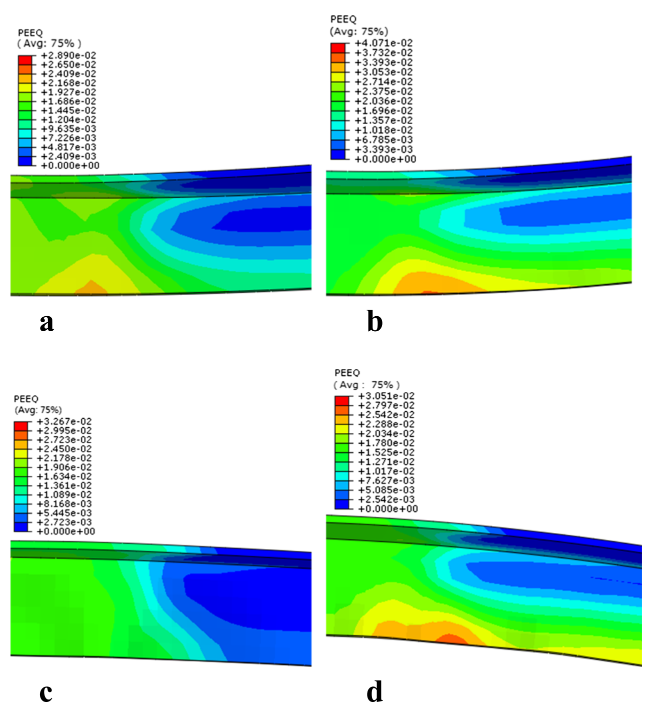

Fig. 11 Equivalent strain distribution of bent angel irons. **a** s = 6 mm. **b** s = 10 mm. **c** s = −6 mm. **d** s = −10 mm

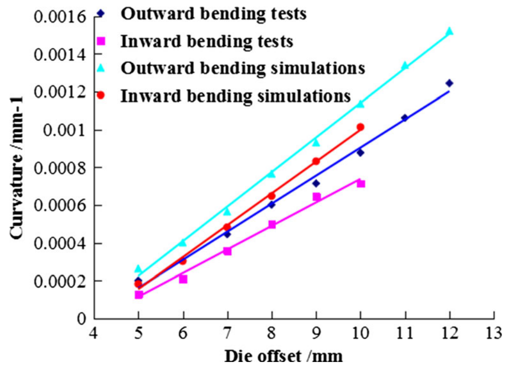

Fig. 12 The influence of die offset on bending curvature

ascribable to the big height-width ratio of the web cross-section, leading to distort to a certain extent for bending instability, which results in a smaller bending curvatures of inward bent angle irons.

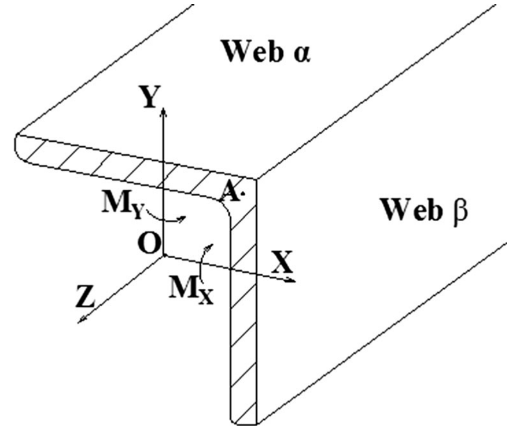

Fig. 14 Force analysis diagram of angle iron section

5 Elimination of side bending defect

5.1 Generation mechanism of side bending

The generation of side bending results from the asymmetry of angle iron section that is the difference between the bending center and the center of gravity of the cross-section [16]. Figure 14 shows the force analysis diagram of angle iron cross-section in outward flexible-bending. Angle iron consists of two perpendicular webs, which are web α and web β. The bending center and the center of gravity of the cross-section are respectively point A and point O.

The bending of angle iron is a combined deformation of bending about X axis and bending about Y axis. In the process of flexible-bending, web α is bent in the YZ plane subjected to bending moment M_X. The cross-section of angle iron is asymmetric about the YZ plane, leading to inequality of moments about Y axis generated by tensile and compressive stress in web β, resulting in generation of another moment M_Y in the XZ plane, which gives rise to bending deformation of web β in the XZ plane, that is, the side bending. When the mechanism is applied to inward flexible-bending, the moment M_X is in the opposite direction, leading to an unequal reversed moment M_Y; the resultant side bending is thereby in the opposite direction.

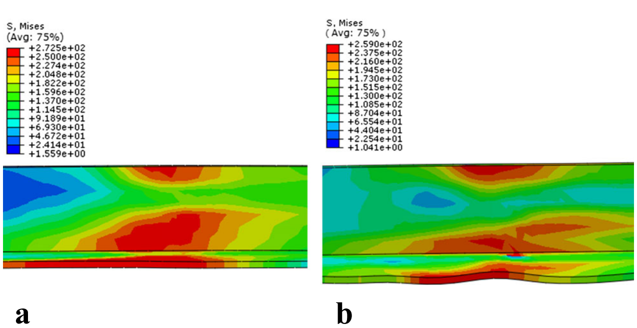

Fig. 13 The stress distribution in deforming region of angle irons. **a** Outward bending. **b** Inward bending

5.2 Curvature of side bending

Figure 15 shows the result of the influence of die offset on side bending curvature. Both the simulated and experimental results indicate that the curvature of side bending in outward bent angle iron is larger than that in inward bent angle iron of same die offset, and curvature of side bending in outward bent angle iron increases more rapidly with the bend die offset. The difference is caused by bending instability in the case of inward bending.

Curvature of bent angle irons and side bending of simulated results are larger than experimental results, which is mainly ascribable to clearances in experimental equipment including clearance between bend die and bearing, clearance between parts in motors and reducers, and so on.

5.3 Elimination of side bending

In the process of flexible-bending of angle iron, the side bending defect can be eliminated by setting die offset in the reverse direction of side bending. The curvature of side bending decreases as the reverse die offset increases, and a critical reverse

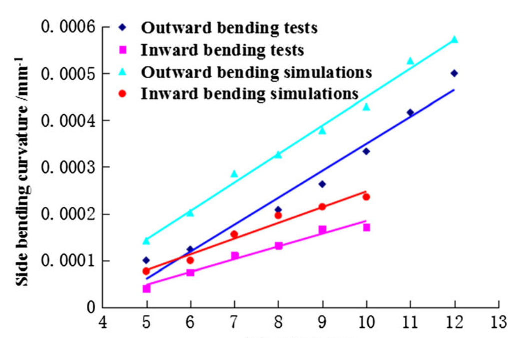

Fig. 15 The influence of die offset on side bending curvature

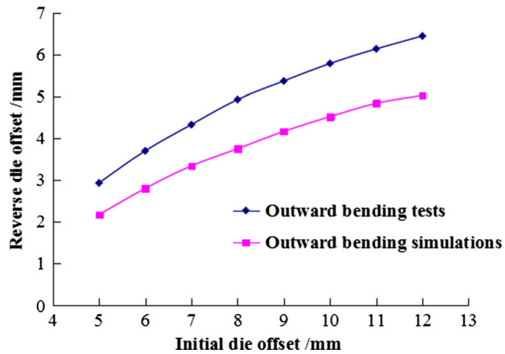

Fig. 16 Die offsets in the reverse direction of side bending

die offset can be obtained to eliminate side bending defect exactly, above which side bending will be overdone to the other side. The effect of reverse die offset on eliminating side bending is analyzed, and the simulated and experimental result of exact reverse die offsets of different initial die offsets is shown in Fig. 16. It is observed that the variation trend of reverse die offset with the initial die offset of simulated results is consistent with experimental results.

With die offset in the reverse direction of side bending, the angle iron cross-section is subjected to an additional force F_X in the minus X direction (Fig. 13), which leads to an additional moment about the Y axis in the reverse direction of M_Y. Side bending can be eliminated exactly when the amount of the additional moment is the same as M_Y and cancel each other.

Figure 17 shows the simulated result of equivalent strain distribution in bent angle irons with and without the reverse die offset. The initial die offset in the Y direction is 9 mm (as shown in Fig. 17a), with reverse die offset of 4 mm being added in the case of Fig. 17b, where the side bending defect is eliminated. It is observed that equivalent strain is larger in angle iron after being rectified by adding reverse die offset, the curvature of which is also larger.

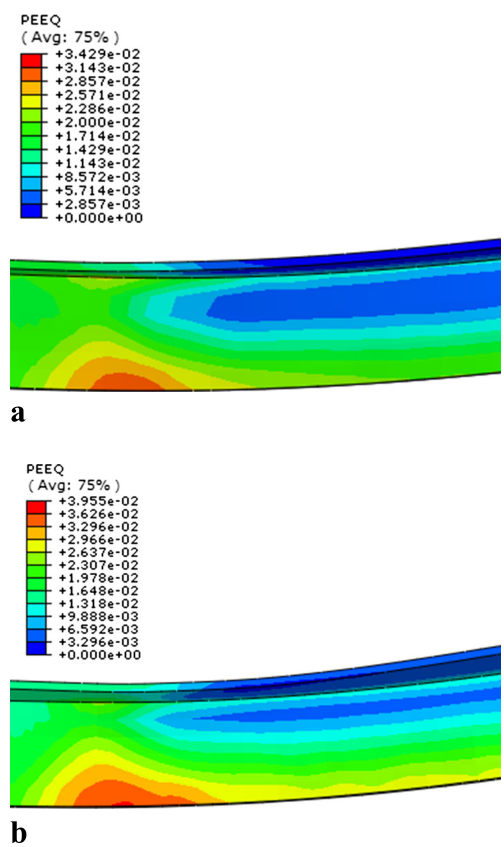

Fig. 17 Equivalent strain distribution in bent angle irons. **a** Bent angle iron without reverse die offset. **b** Bent angle iron with reverse die offset

6 Conclusions

1. Flexible-bending method can be applied to bend profiles with asymmetric cross-section.
2. In the flexible-bending process, angle irons of different curvatures can be obtained by shifting the bend die. Outward bent angle iron and inward bent angle iron are thereby obtained by shifting the die in the plus and minus Y direction, respectively, and the curvatures of bent angle irons increase linearly with the die offsets.
3. The side bending defect of bent angle iron is ascribable to the difference of the bending center and the center of gravity of the cross-section. The curvatures of side bending increase linearly with die offsets and the curvatures of outward bent angle irons are larger than that of inward bent angle irons.
4. The side bending defect can be eliminated by shifting the die in the reverse direction of side bending.

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