Numerical Analysis of Circular Pre-notched U-Channel Section Distortions in Cold Roll-Forming Process

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Abstract: Cold roll forming is a process in which a metal sheet gets a desired section form by passing through a series of rotating rollers. Predicting the amount of the distortion in pre-notched cold formed sections still remains challenging in cold roll forming industry, depending on the shape and position of the holes. This study investigates the influence of variation of the design parameters on the defects of the U-channel sections produced by cold roll forming process with circular pre-notches. To analyze the important parameters in deforming the circular holes during the cold roll forming of U-channel sections, a three-dimensional finite element model has been taken into account. A range of variation for design factors in forming the U-channel sections with pre-notches is set, including radius of circular holes, distance between the holes and the flange edge, hole spacing, sheet thickness, and type of material. Furthermore, using the response surface methodology, a set of tests are designed and modeled employing Finite Element analysis. Afterward, a set of output parameters such as edge buckling, the wave of the holes, the change in hole size, hole spacing, and the distance between the holes and the edge of the flange, are considered. Utilizing Analyses Of Variance (ANOVA), the accuracy of the linear regression models was conducted in this study. The accuracy of the simulated models is examined by comparing the analysis results with the experimental results. Finally, the effect of the important parameters on the defects of the product has been extracted in both the statistical form as well as mathematical functions applying response surface methodology. The results show that as the radius of the hole increases, edge buckling increases. The increase of the hole radius increases the edge wave on the holes. The hole width of the product is bigger and the hole length is smaller than the nominal measuring.

Keywords: Cold Roll Forming, Finite Element, Pre-notched Sheet, Response Surface Method, U-channel Section

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1 INTRODUCTION

In cold roll forming process, a raw metal sheet is formed into a final profile by passing through a range of forming stations without change in thickness [1]. This process is rather complicated due to the deformation of the sheet between the forming stations and during engagement with the rollers [1]. Therefore, understanding the distortion mechanism in the cold roll formed products is important. The products produced by cold roll forming process are applied in automotive and refrigerator manufacturing industry. A large number of studies have been conducted in recent years to shed light on different aspects of this issue, among which some are summarized here. Design of the cold roll forming process is based on the experimental rules and designers' experiences [2]. The number of the forming stations depends upon the complexity of the section and the nature of the sheet deformation [1].

Early models of cold roll forming process were designed by Bhattacharyya et al., [3] and Chiang [4]. The model of Bhattacharyya et al., [2] was achieved based on longitudinal deformation with minimizing plastic work for the U-channel section. Their model predicted that the length of deformation was independent of yield strength. Later, a valid general numerical method was proposed for the arbitrary section by Brunet et al., [5]. This model made a progress in modeling of the cold roll process and it is still cited. It aims at achieving an improved function for designing roll profile based on rubber plastic finite element method. Watari and Ona [6] analysed the features of defect shapes in cold roll forming of the pre-notched products of V-channel and U-channel sections as well as tube profiles. They defined a range for dimensions of cross-sections and pre-notches for experiments, and compared the results. Watari and Ona [6] concluded that edge wave (Figure 1) is higher in the products with high flange length compared to that of low flange length ones. Experimental study, conducted by Ingvarsson [7] on comparison between mild and high strength steel in V-channel sections, reported that high strength steel needs less forming stations compared with mild steel. Han [8] studied the effects of forming parameters on the U-shaped cross sections. Finally, the results revealed that increasing the bend angle between two stations increases the yield limit of the maximum longitudinal membrane strain material of the cross section. Salmani Tehrani et al., [2] used FE simulation to predict edge buckling as a limiting factor in cold roll forming of a symmetrical section. The results of his simulations indicated that in rolling process, the bend angle in the first stations should be less than a certain limit; otherwise, edge buckling will occur in the next stations. Lindgren [9] used Finite element simulation and evaluated the effects of yield strength on the maximum longitudinal strain and length of deformation. They indicated that strain will decrease when yield strength is increased. In addition, the more is the length of deformation the more will be the yield strength. Using simulation of the cold roll-forming process by finite element method, Bui and Ponthot [10] analysed spring back phenomenon of the process and the results indicated that the amount of spring back during the process in high strength materials is higher than mild materials. Zeng [11] obtained mathematical models that represent the effect of forming angle increment and roll radius on spring back angle and maximum edge membrane longitudinal strain by applying response surface methodology in order to optimize the design of cold roll forming process. Moslemi Naeini et al., [12] applied the data acquired from simulations of the finite element method. He investigated the reasons of creation of the surface defects in the produced pre-notched U-channel section by cold roll process. He classified the reason in certain groups and explained the amount of effects of each parameter on the defects. Finally, he concluded that, in cold roll forming of the per-notched sections, by increasing the diameter of the circular hole on the flange of the U-channel section, wrinkles of the profile edge increases. Furthermore, adding to the number of the formation processes decreases the geometrical defects of steel profiles.

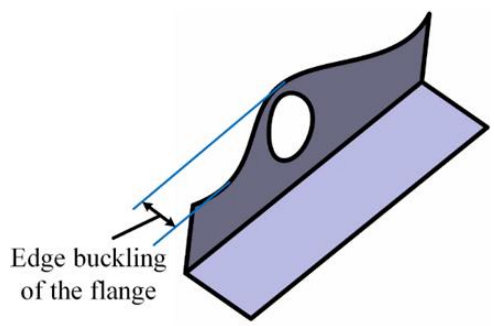

Fig. 1 Schematic of edge wave defect [1]

This study analyses and simulates the effective process parameters in deformation of the holes during the cold roll process using a set of finite element simulations. The U-channel sections with circular holes on the flange are simulated using FE models. Afterward, a feasible range is considered for the design factors such as the radius of the hole, the hole spacing on the flange, the distance between the holes and the edge of the flange, sheet thickness and the material strength of the sheet. Furthermore, applying response surface method and determining the constraining situations on the design factors, the required experiments for analysing the process were designed and simulated. Subsequently, the purposed functions such as buckling, edge wave, and the change in the geometric size of the product in relation to the nominal size were measured. The accuracy of the results is evaluated by ANOVA and the results, achieved from the simulations, were analysed by response surface methodology.

2 TYPES AND MEASUREMENT OF DEFECTS IN THE PRE-NOTCHED U-CHANNEL SECTIONS

Various defects can be defined in the pre-notched U-channel sections without holes including edge buckling, bending, twist, and edge wave [13]. In addition, the holes on the section can create more defects because the hole acts as a center of tension concentration. In this study, defects are categorized into two groups: 1) Buckling and wave defects 2) Geometric deformation defects.

2.1. Buckling and wave Defects

One of the significant defects of the U-channel sections is the edge buckling of the flange, as shown in Figure 2. For measuring, the amount of edge buckling of the product is measured in relation to the parts of the edge on which less buckling is imposed. In fact, maximum height of the created edge wave on the edge of the flange is measured.

The edge buckling of the flange occurs due to the difference in the longitudinal strains on the web and edge of the product, where a high longitudinal strain exists on the edge in lieu of a low strain along the bend line. Therefore, buckling could be seen on the edge of the product [2].

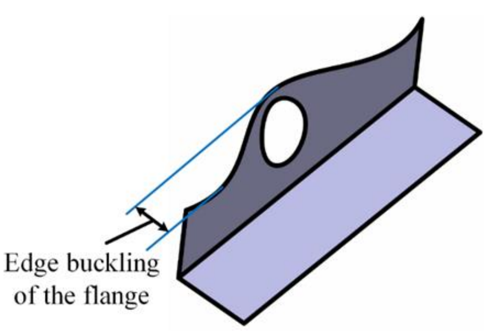

Fig. 2 Edge buckling of the flange

To measure the wave on the holes of the product, the hole is divided into 4 parts, shown in Figure 3, and the maximum of the height of the edge wave for each part is measured separately. Finally, average of four parts is calculated as the edge wave on the hole. To illustrate, in the light of hole positions on the edge of the flange, hole spacing and proximity of the holes to the bending line and flange edge, the most amount of deformation and edge wave occur in one or a number of considered sections. Therefore, in order to obtain a standard and coordinated model for comparing the overall deformation and edge wave of the holes, the average of waves, height of waves, in four intended equal sections of the holes, close to the edge, bending line and adjacent to each other, are measured and expressed as the final amount of edge wave. Various defects can be defined in the pre-notched U-channel sections without holes including edge buckling, bending, twist, and edge wave [13]. In addition, the holes on the section can creates more defects because the hole acts as a center of tension concentration. In this study, defects are categorized into two groups: 1) Buckling and wave defects 2) Geometric deformation defects.

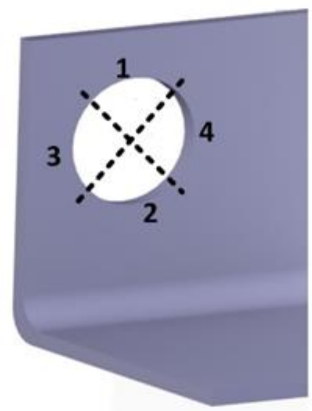

Fig. 3 Dividing the hole into four parts to analyze the edge wave on the hole of a U-channel section with circular hole

2.2. Size Change Defect

The width and length of the holes in U-channel sections are different from the nominal values (Figure 4) because of the forces applied on the section in the production process. The width and length of the holes are defined in accordance with Figure 5. Similarly, the hole spacing and the distance of the hole from the edge of the flange are different from what is defined for experiment design. The hole spacing on the flange and the distance between the holes and the edge of the flange are shown in Figure 5. Size change defect is also caused by the difference in the longitudinal strains on the flange of the product [9].

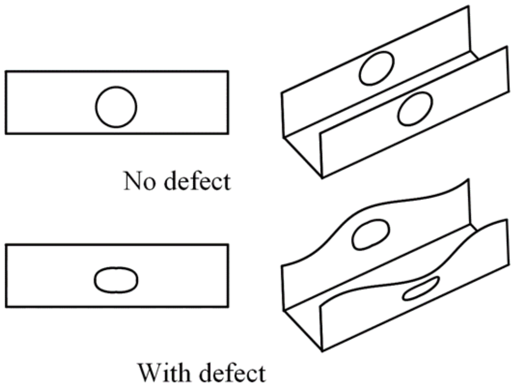

Fig. 4 Deformation of holes

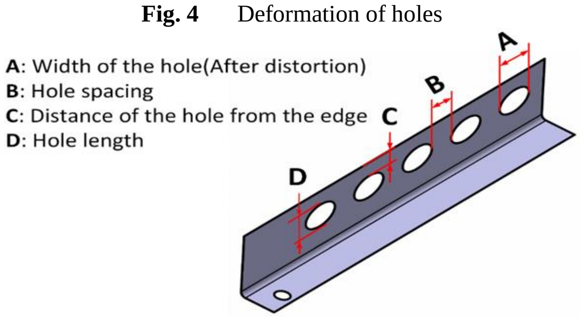

Fig. 5 Illustration of the distance between the holes and the edge, the hole spacing, the width and length of the hole on half of the U-channel section with circular holes

3 FINITE ELEMENT MODELING AND ANALYSIS

A three-dimensional finite element model of the cold roll forming of the pre-notched U-channel section is created as shown in Figure 6. Furthermore, the deformed shape of the sheet in each station as the flower pattern is shown in this Figure. To illustrate, the flower pattern indicates the cross-section of sheet in deferent forming stations, simultaneously. There are seven forming stations in this simulation. The gap between upper and lower rollers is equal to the sheet thickness. Table 1 summarizes the various parameters of the models.

Table 1 The process designing factors

Factors	Values
Distance between forming stations	300 (mm)
The diameter of upper rollers	120 (mm)
The diameter of lower rollers	60 (mm)
Rotational velocity of the rollers in station 1	0.3(m/s)
Sheet size	43.5 (mm)×600 (mm)
Deformation in each station	30, 45, 60, 75, 85, 90 (degree)

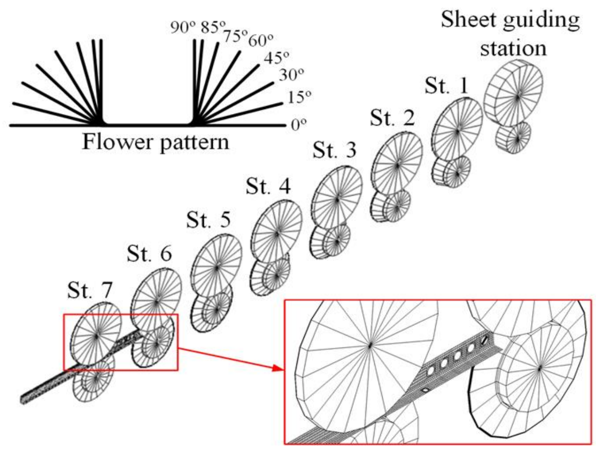

Fig. 6 Illustration of the finite element model created for the cold roll forming of the pre-notched U-channel section

The upper rollers in the finite element model are flattened. The finite element model includes half of the forming process due to symmetry. The first two rollers function as conductors of the sheet. Five circular holes are created on the edge of the flange and the modeled sheet with nominal size is shown in Figure 7.

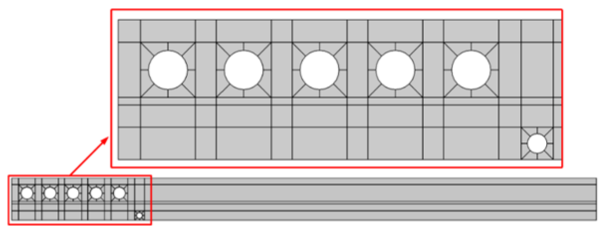

Fig. 7 The modelled sheet with circular holes

Three materials were employed for the simulation. Mild steel SA1020 is used for material 1. For the material 2 and 3 as the medium and hard material, the amount of mild material stress of 100 MPa and 200 MPa were added respectively, with the same base strain. To illustrate, In order to investigate the effects of material strength on the defects of the product, the stress strain diagram of SA1020 steel, as a mild steel, is offset as much as 100 MPa and 200 MPa to achieve a medium and hard steel, respectively. Indeed, in order to avoid the variation of the curve slope in the area of plastic, the offsetting is carried out. By the same token, the amount of stress is increased only. The features of the mild steel SA1020 are reported in Table 2.

Table 2 Material properties of the mild steel SA1020

Feature	Amount
Young's modulus	207Gpa
Poisson's ratio	0.3
Density	7800 kg/m^3
Stress-Strain model	$\sigma = 617.2\varepsilon^{0143}$
Hardening coefficient (K)	617.2Mpa
Offset strain	0.001292

Hardening exponent (n)	0.143

3.1. Mesh Characteristics

Rollers in rigid form and sheets with shell element of S4R are modelled. In order to have more accuracy, sheets are partitioned in hole area and bend one, surround the bend line, which are indicated in Figure 8. , the independency of mesh is evaluated for the analysed model considering the deformation energy. In addition, coefficient of friction is 0.2 for all of the rollers. As can be seen in Figure 7, a hole near the symmetry line is considered to investigate the effect of the design factors on the defects of the holes at the web of the U-channel section. Investigations show that the design factors do not have significant effects on the distortion of the holes at the web of U-channel sections.

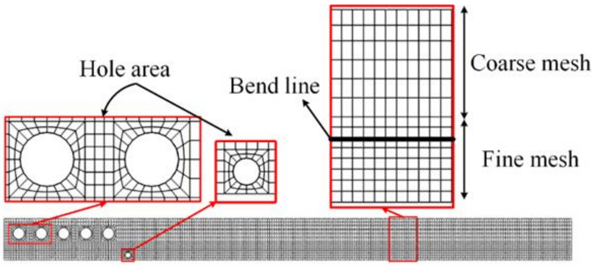

Fig. 8 The Meshed sheet with circular holes

3.2. Boundary Conditions

To reduce the analysis time, only half of the process is modelled considering the symmetry of the process, with the symmetric boundary condition along the symmetry line. The rollers are constrained against the displacement, rotation, angular velocity, and velocity. The velocity of the linear motion for the first forming station is considered as 5 rpm and 10 rpm for the upper and the lower rollers, with 5% increase at each stage of the formation because of creating a relative stretch on sheets between the stations to prevent the wrinkles of sheets. Moreover, coefficient of friction has been considered 0.2 with surface-to-surface contact as the type of interaction between the rollers and the sheet.

3.3. Analysis

The analyses are carried out by Abaqus.6.11.3 software in Dynamic Explicit form. In the analyses, the first two initial rollers have the function of conducting the sheet. In the first stage of the forming process, the lower roller is embedded in a distance of 20 mm plus the sheet thickness from the upper roller. The lower roller moves close to the upper roller with only the sheet in between and brings about the appropriate involvement of the sheet and the rollers. Then, the rollers in station 1 start to move with the initial velocity. With the proper timing, the rollers in station 2 begin to rotate before head of the sheet reaches to this station. This process makes the sheet and roller be involved appropriately proceeding to the last station.

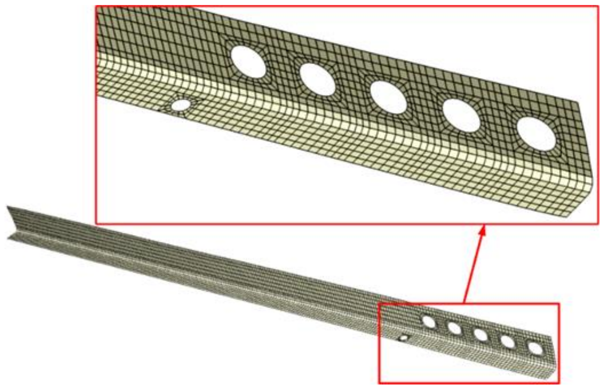

Fig. 9 The final product of simulation

In these analyses, the kinetic energy is less than 10% of the internal energy, which confirms the validity of the quasi-static model. The final product obtained from the simulation is shown in Figure 9.

4 THE EXPERIMENT DESIGN

The response surface methodology is employed to design the experiments. First, the design factors which are introduced in table 3 are considered. Subsequently, the responses are considered as the output parameters. The responses are defects of the pre-notched U-channel section as mentioned in section 2 and 4-2. The designed experiments with the introduced factors are modelled. The responses that are taken into account are measured for each experiment. Finally, the results are analysed and the effects of the design factors on the responses are determined. The measuring process of the responses is mentioned in section 2.

4.1. Input Parameters

In order to determine the simulation correctness and the design factors, a number of initial simulations are carried out. The input design factors include: i) The radius of circular holes, ii) The distance of the holes from the flange edge, iv) hole spacing, v) Sheet thickness, and vi) Type of material. The range of these variables are reported in Table 3. The range is achieved after several initial simulations.

Table 3 Range of the variation for design factors.

Design factors	Constraint range
The radius of circular holes	3.5-7.5mm
The distance of the holes from the flange edge	2-9.5mm
Hole spacing	10-70mm

Sheet thickness	1-4mm
Type of material	1:Mild, 2:Medium, 3:Hard

4.2. Output Parameter

The output parameters include the change in the width and length of the hole, edge buckling, edge wave on the hole, the change in the distance between the hole and the edge of the flange and the change in the hole spacing on the flange. Figure 10 indicates the analysis of variance table, related to the investigation of edge buckling of the flange. As can be seen in Figure 10, the results are accurate in terms of statistics and analysis of variance. Indeed, p-value is the standard method looking for significant terms to keep or insignificant terms to remove from the model. Furthermore, p-value should be less than 0.5 in order to be significant [14]. Table 4 indicates the ANOVA for the results of the edge buckling in the U-channel sections with circular holes, proceeded by Design Expert 9. Similarly, the analysis of variance is conducted for other defects and output parameters.

Table 4 Analysis of variance

Response	Edge Buckling (mm)
Source	Model
Some of Squares	0.69
Mean Square	0.046
F Value	0.046
P Value	0.0009

5 RESULTS

In order to validate the simulation of the finite elements, a set of experiments conducted by Shirani [15] is modelled and the results are compared with the experimental results. Shirani et al., [16] investigated experimentally the effects of the geometrical variables of circular pre-notched U-channel products and the roll forming variables on the ovality of holes in the U-shaped sections. The circular pre-notched U-channel tested by Shirani [15] is modelled with a flower pattern of 0, 30, 60, 90 degrees. Variation of the edge buckling of the flange, computed in the finite element model, are plotted in Figures 11 and 12 and compared with the experimental results of the Shirani [15] tests.

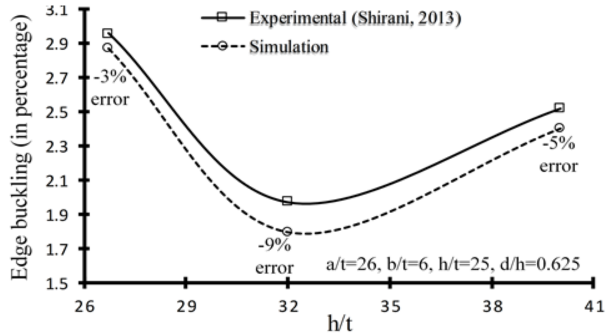

Fig. 10 The variation of the edge buckling with respect to the size over thickness of channel

In Figure 10 and 11, a is the hole spacing, b is the distance of the holes from the edge of the flange, h is the height of the flange, w is the width of the channel bottom, and t is the sheet thickness.

5.1. Edge Buckling of the Flange

Effects of the design factors on the variation of the hole radius in the final product are analysed. Analysis results show that the buckling increases as the hole radius increases due to the decrease of the flexural stiffness (Figure 12). Dot bands in Figures 12-26 are the confidence bands clarifying the range of variation for measured output parameters as the defects of the products.

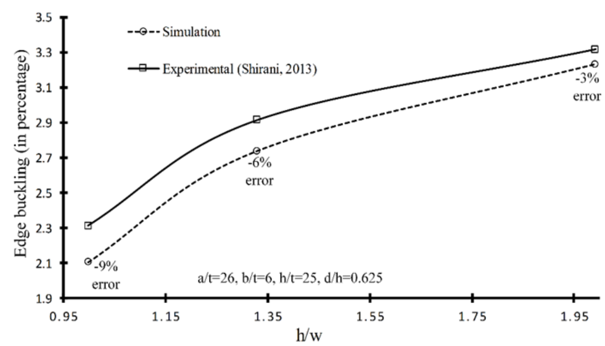

Fig. 11 The variation of the edge buckling with respect to the proportion of walls to the bottom of the channel

Eq. (1) is achieved based on the response surface methodology, and predicts the edge buckling of the circular pre-notched U-channel section, R_1, based on the design factors, A, radius of the hole; B, the distance between the hole and the edge of the edge; C, hole spacing; D, sheet thickness and E, type of material.

$$R_1 = 0.158 + 0.054A - 0.025B + 0.0007C + 0.005D - 0.057E \quad (1)$$

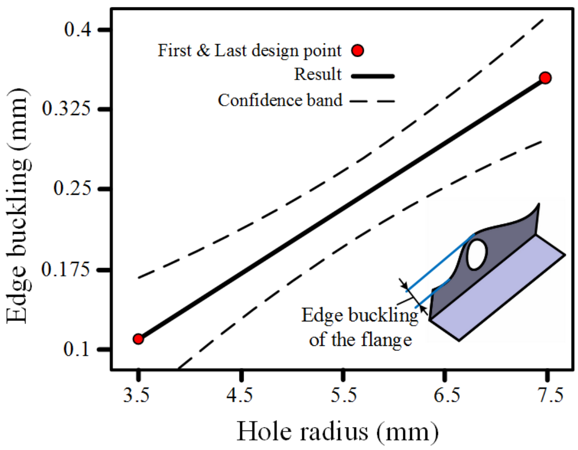

Fig. 12 The variation of the edge buckling with respect to the radius of the hole

5.2. Wave on the Edge of the Hole

To analyse the edge distortion of the holes more accurately, the sector of the hole is divided into 4 sections (Figure 3), and the magnitude of the wave on the edge is computed as the average of measured values at the upper and lower parts as well as the sides. Figure 13 shows that as the hole radius increases, the edge wave increases, because of the decrease in the flexural stiffness of the sheet. Eq. (2), which has been obtained based on response surface method, predicts The wave on the edge of the circular pre-notched U-channel section, R_2, based on the design factors.

$$R_2 = 0.15 + 0.04A - 0.01B - 0.0002C - 0.025D + 0.023E \quad (2)$$

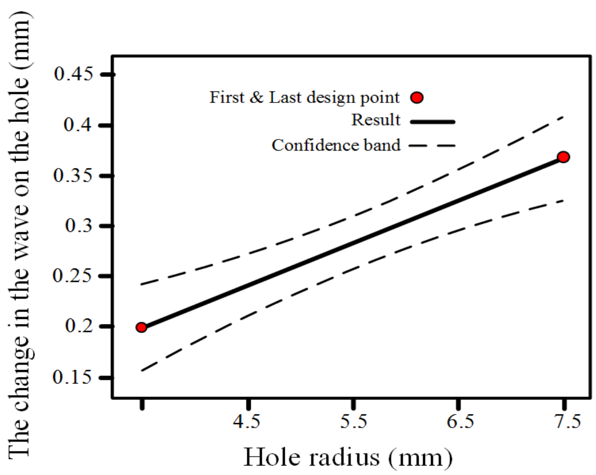

Fig. 13 The Change of the wave on the hole in relation to the hole radius

5.3. Change in the Size of the Holes

Measuring of the hole width and length in the final products shows an increasing trend in the width of the holes compared with the nominal size, as shown in Figure 14. Furthermore, the measured length of the holes in the final products revealed to be less than its nominal value. The resulted deformation is attained due to the progressive increase in speed of each station in proportion to the previous station.

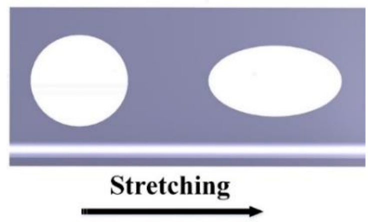

Fig. 14 The change in the size of a hole before and after forming

5.3.1. Change in the Width of the Holes

Effects of the design factors on the change in the width of the holes in the final products are analysed. Analysis results show that as the radius of the hole increases the width of the hole increases (Figure 15). Furthermore, the distance between the hole and the edge of the flange increases, the width of the hole become closer to the nominal value, as shown in Figure 16. However, as the hole spacing on the flange increases, the width of the hole increases, as shown in Figure 17. Moreover, analyses of results show that as the sheet thickness increases, the width of the hole increases (Figure 18) due to the decrease of the spring back in the thicker sheet.

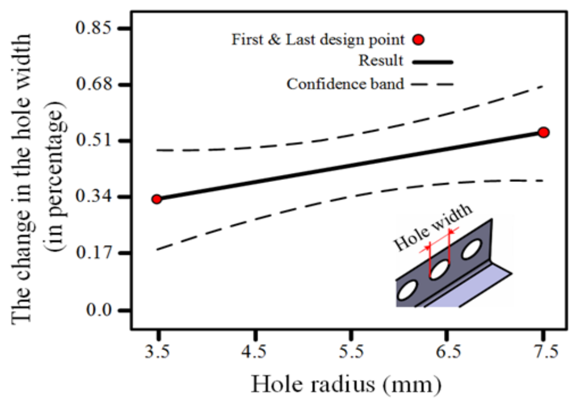

Fig. 15 The change in the width of the hole (in percentage) with respect to the radius of the hole

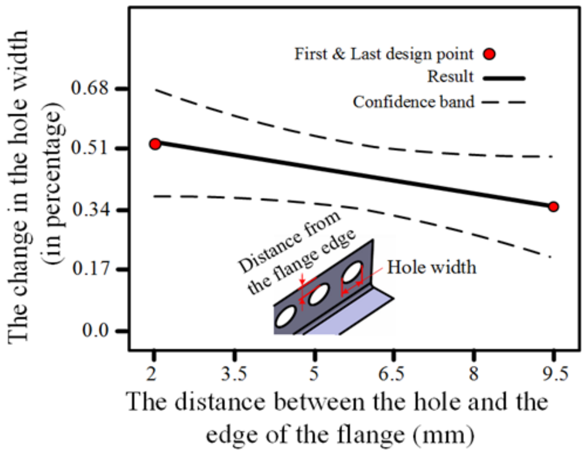

Fig. 16 The change in the width of the hole (in percentage) with respect to the distance between the hole and the edge of the flange

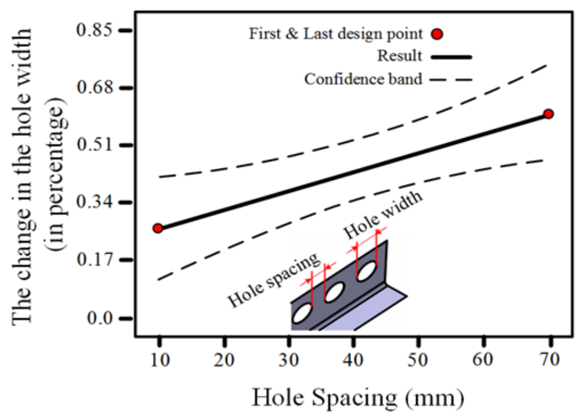

Fig. 17 The change in the width of the hole (in percentage) with respect to the hole spacing on the flange

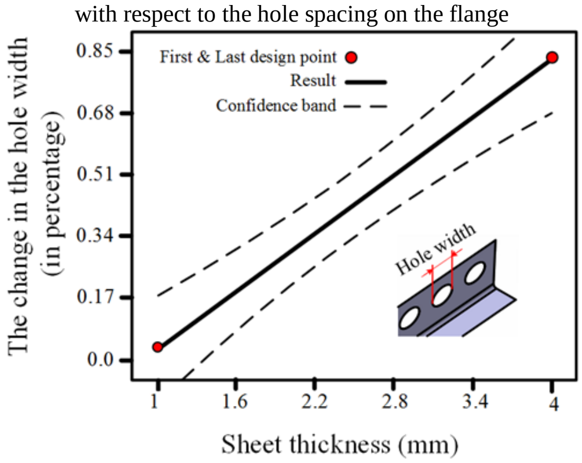

Fig. 18 The change in the width of the hole (in percentage) with respect to the sheet thickness

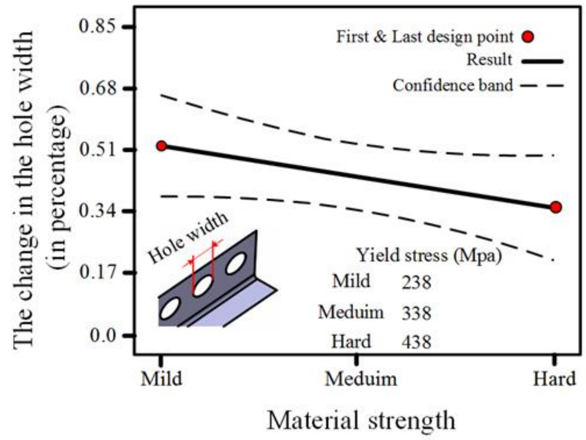

Fig. 19 The change in the width of the hole (in percentage) with respect to the material strength

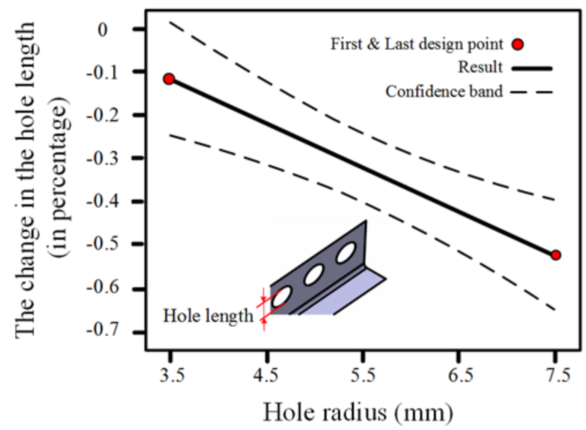

Fig. 20 The change in the width of the hole on the flange (in percentage) with respect to the radius of the hole

Figure 19 shows that as the material strength increases, the width of the hole becomes closer to the nominal value due to the increase of spring back of the higher strength material. Eq. (3) is computed based on the response surface methodology, and predicts the change in the width of the holes on the flange of the U-channel sections, R_3, based on the design factors.

$$R_3 = -0.422 + 0.050A - 0.023B + 0.006C + 0.263D - 0.085E \qquad (3)$$

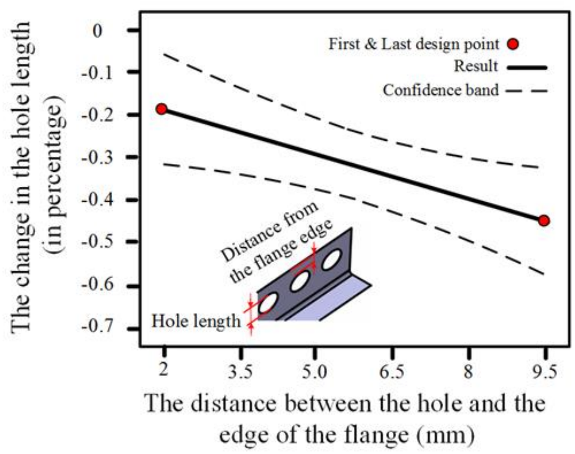

Fig. 21 The change in the width of the hole on the flange (in percentage) with respect to the distance between the hole and the edge of the flange

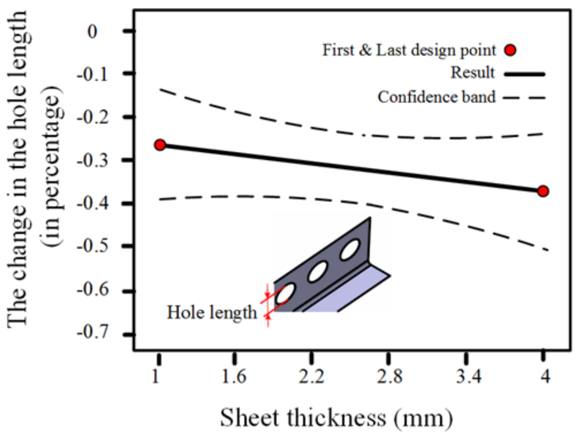

Fig. 22 The change in the width of the hole on the flange (in percentage) with respect to the sheet thickness

5.3.2. Change in the Length of the Holes

The effects of the design factors on the change in the length of the holes in the final products are investigated. The results reveal that as the nominal radius of the holes, the distance between the hole and the edge of the flange and sheet thickness increase, the length of the holes decreases (Figure 20, 21, 22). Moreover, as the hole spacing and the material strength increase, the length of the holes becomes closer to the nominal value (Figures 23, 24). Eq. (4) is computed based on the response surface methodology, and predicts the holes length changes on the flange of the U-channel sections, R_4, based on the design factors.

$$R_4 = -0.599 + 0.02G - 0.02B + 0.011C + 0.329D - 0.086E \quad (4)$$

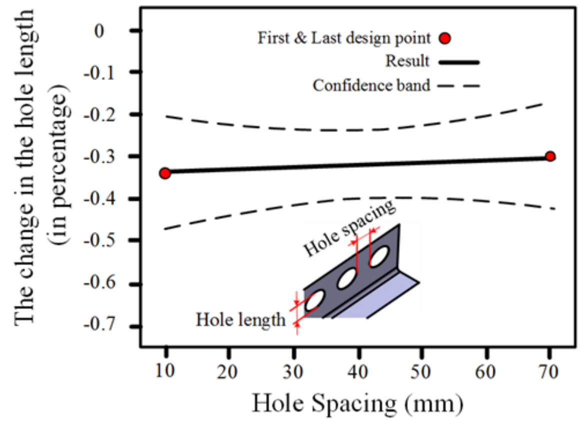

Fig. 23 The change in the width of the hole on the flange (in percentage) with respect to the hole spacing on the flange

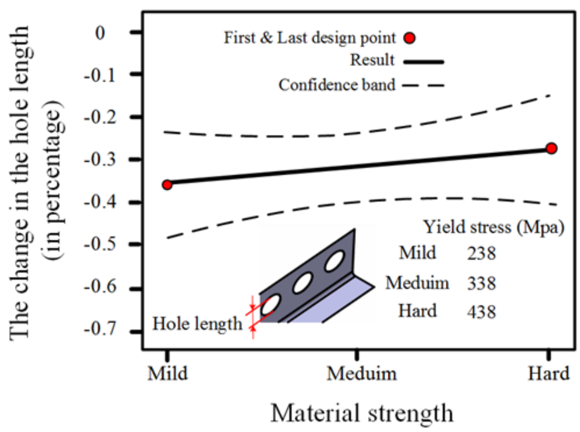

Fig. 24 The change in the width of the hole on the flange (in percentage) with respect to the material strength

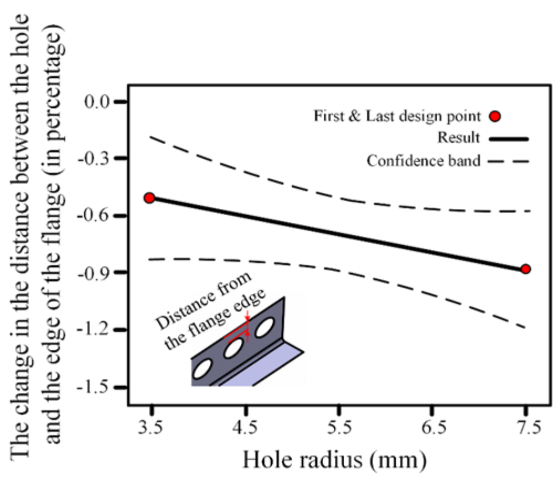

Fig. 25 The variation of the distance changes from the flange edge (in percentage) with respect to the hole radius

5.4. The Change in the Distance between the Holes and the Edge of the Flange

The observation of the modellings demonstrates that the distance between the hole and the edge of the flange is less than the nominal size. In fact, the holes get closer to the edge of the flange in the final products in comparison with the nominal size. Basically, due to the engaging of rollers at the time of rolling of sheets, the linear speed of the forming is higher at the points which are closer to the edge of the flange, while the speed of the rollers increases in each forming station in comparison with the previews station, which in turn leads to further traction on the edge of the product. Analysis of results shows that as the radius of the hole increases, the distance between the hole and the edge of the flange decreases (Figure 25).

Equation 5 is achieved based on the response surface methodology, and predicts the change in the distance between the hole from and the edge of the circular pre-notched U-channel section, R_5, as a function of the design factors.

$$R_5 = 0.336 - 0.094A + 0.057B - 0.002C - 0.355D + 0.068E \quad (5)$$

5.5. The Change in the Hole Spacing on the Flange

The observation of the modellings shows that the hole spacing on the flange of the products is more than the nominal value (Figure 26) due to the progressive increase in speed of each station in comparison with the previous station. Analysis of results show that as the radius of the hole increases, the hole spacing becomes closer to the nominal value. Eq. (6) predicts the variation of the hole spacing on the flange of the circular pre-notched U-channel section, R_6,based on the design factors, by applying response surface methodology.

$$R_6 = -0.0319 - 0.001A + 0.002B + 0.0005C + 0.013D - 0.004E \quad (6)$$

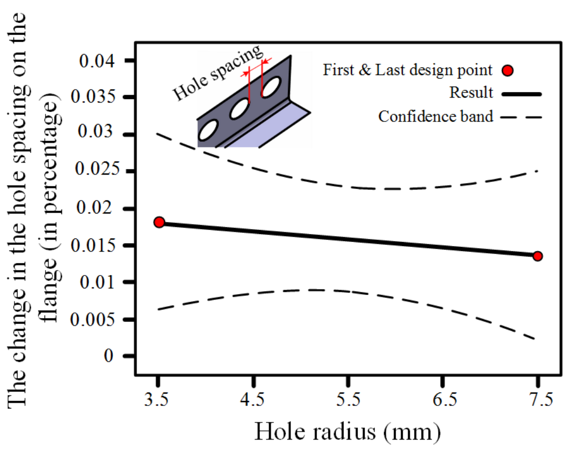

Fig. 26 The change in the hole spacing on the flange (in percentage) with respect to the radius of the hole

6 CONCLUSION

In this study, the effect of changes in designation factors of the pre-notched U-channel sections in cold roll forming process on the geometrical defects is investigated by the data analysis of the experiment designs including 31 simulations. Indeed, the effect of the design factors on the defects of the product has been extracted in both the statistical form as well as mathematical functions, predicting the defects of the product, by applying response surface methodology. The key findings of this study for the circular, pre-notched cross-sections are as follow:

As the radius of the hole increases by 114%, edge buckling increases by 160% in the U-channel sections with circular pre-notched. The increase of the hole radius by 114%, increases the edge wave on the holes by 78% in the U-channel with circular pre-notched.

Thereupon, the findings justify the variation in the shape of the holes in the final U-channel product. The observed changes determine that the hole width of the product is bigger than the nominal measuring and the hole length is smaller than the nominal measuring. As the nominal radius of the holes, the hole spacing and the sheet thickness increase, the width of the hole increases in relation to the nominal measuring. Moreover, as the distance of the hole from the edge and material strength increase, the width of the hole decreases.

Furthermore, as the nominal radius of the hole and the distance between the hole and the edge and sheet thickness increase, the length of the hole decreases in relation to the nominal value. Also, as the hole spacing on the flange and the material strength increase, the length of the hole becomes closer to the nominal value.

The distance between the holes and the edge of the flange is always less than the nominal amount. In fact, the holes get closer to the edge of the flange. Analysis of the results show that as the radius of the hole increases, the hole spacing on the flange and the distance between the hole and the edge decrease.

The hole spacing on the flange are more than the nominal amount. As the radius of the hole increases the hole spacing gets closer to the nominal value.

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