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Optimal Boundary Shape of the Center-Reduced Cruciform Specimen for the In-Plane Biaxial Test

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Abstract. Cruciform specimens are one of the most common used to measure the plane mechanical properties of materials. Two significant difficulties in designing cross specimens are reducing stress concentration at the intersection of cross arms and improving stress/strain uniformity in the gauge area. The shape of the border at the intersection of the cruciform specimen is tightly related to the above two. Due to the lack of guidelines for the design of cruciform specimens, optimizing the cruciform specimen border intersection is an urgent problem to be solved to increase the reliability of test results. By employing the finite element method and the shape optimization method, the boundary of the cruciform specimen is optimized, and the mathematical expression of the shape function at the intersection of the cruciform specimen's boundary is obtained. Furthermore, experiments are used to validate the optimum border. The findings indicated that the stress concentration at the improved specimen's boundary was reduced. The optimal shape of the cruciform specimen's boundary intersection described in this study can be used as a reference for the structural design of the cruciform specimen and can be used for extensive strain testing of the cruciform specimen.

Keywords. Cruciform specimen stress concentration, optimal shape, in-plane biaxial test, specimen design

1. Introduction

Multiaxial testing of material is essential for confirming the theory of multiaxial strength. The reliability of material multiaxial test results determines the reliability of the material strength theory. The in-plane biaxial test is an effective method for determining a material's in-plane mechanical properties. The structural form of the cruciform specimen is directly related to the in-plane test results. Due to the lack of design standards for cruciform specimens, there is no agreement on the structural form of these specimens, which results in a wide variety of material test results [1]. Our goal is to develop high-precision in-plane biaxial testing equipment and optimize the

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structure of cruciform specimens in order to improve the theory and practice of in-plane biaxial testing.

The in-plane biaxial test results highly depend on the cruciform specimen's structure. The stress concentration at the crossarm intersection of the cruciform specimen causes failure to occur before the gauge zone, limiting the in-plane biaxial large strain test [2]. Due to the distinctive cross structure of the cross-shaped specimen, the stress/strain concentration at the intersection of the cross arms is unavoidable. The stress concentration at the boundary intersection of the cross shaped specimen and the stress / strain uniformity in the gauge area are very sensitive to the mechanism parameters of the cross shaped specimen [3]. Even for the same material, the test results of different specimens will have large deviations. In order to obtain reliable biaxial test results of materials, advanced optimization technology is required to optimize the structure of the cruciform specimen.

Utilizing a finite element approach to carry out the structural design of cruciform specimens is an efficient process [4, 5]. The structural optimization design of cruciform specimens by finite element method has yielded fruitful results based on the parameter optimization method: the stress concentration factor at the intersection of cross arms has been reduced; the uniformity of stress/strain in the gauge area has been effectively improved [6, 7]. However, because the parameter optimization method cannot change the geometric dimensions' force transmission properties, the result is simply a locally optimal solution based on the optimized geometric features [8]. The likelihood of reaching the optimal global solution can be raised by optimizing the structural dimensions of cruciform specimens using nonparametric approaches to break through the restriction of geometric parameters on the structure of cruciform specimens.

Optimizing the boundary of the crossarm intersection of the cruciform specimen is necessary to improve the method and theory of the in-plane biaxial test. Using the finite element method and the shape optimization algorithm, we optimize the shape of the crossarm intersection of the cruciform specimen and derive the mathematical expression of the boundary shape to reduce the stress concentration at the crossarm intersection. Experiments validate the optimized border. The results of simulations and experiment showed that the stress/strain distribution at the junction of strain boundaries can be significantly improved with the shape-optimized boundary. The method presented in this research could serve as a reference for the design of cruciform specimen and be used to perform a in-plane biaxial extensive strain test.

2. Methods and Experiments

To reduce stress concentration at the crossarm junction, we first optimize the shape of the crossarm intersection using the finite element approach and shape optimization algorithm and then use curve fitting technology to obtain the mathematical expression of the crossarm intersection. Furthermore, an MTS plane biaxial testing equipment was used to test the optimized cruciform specimen.

2.1. Shape Optimization

The center reduced cruciform specimen is used in the original specimen, as shown in figure 1. The original specimen's length, width, and thickness are 220 mm, 220 mm, and 5 mm. The fillet at the cross arms junction is 10 mm; the specimen clamping position's length, width, and thickness are 40 mm, 40 mm, and 5 mm, respectively. The reduced area is in the center with 35 mm length and width and 1.5 mm rounded corners.

The quarter model was used to optimize the cruciform specimen's border. Figure 2 depicts the shape optimization model's finite element model. The model is organized into three components in figure 2: clamping area, gauge area, and design area. For modeling the equal tension, we rigidly coupled reference points RP1 and RP2 with the clamping area and simultaneously displaced RP1 and RP2 by 0.05 mm each.

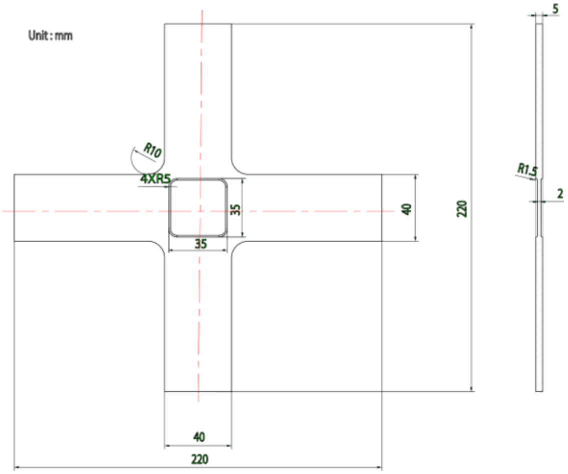


Figure 1. Original Specimen.

According to figure 2, the finite element model is established. Q460, high-strength steel, is the material used for the finite element simulation. Its elastic model, yield strength, and Poisson's ratio are 210GPa, 460MPa, and 0.3. The finite element model comprises 28517 nodes and 22936 elements of C3D8R.

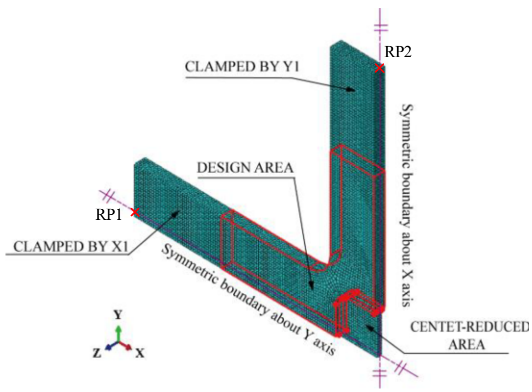


Figure 2. Shape Optimization.

We establish the optimization parameters area, objectives, and constraints. Additionally, the following modifications were made: Freeze the clamping end elements and orient the Z-axis in the direction of element removal.

The following is the objective of topology optimization:

$$min\{ \sum E(\rho_e, u_e) \} \tag{1}$$

where

E—The strain energy of each element in the design area;

ρ_e—The reduction factor of the material density of each element in the design area;

μ_e—The displacement of each element in the design area.

The following are the constraints of topology optimization:

$$\sum_{e=1}^{n} v_e \rho_e \leq \alpha V_{initial} \text{ , } 0 \leq \rho_e \leq 1 \tag{2}$$

where

v_e —The volume of each element in the design area;

α —The friction coefficient of the design area's initial volume;

$V_{initial}$—The displacement of each element in the design area.

2.2. Experimental Validation

We use an MTS biaxial test system to validate the strain distribution at the optimized specimen's crossarm intersection.

Table 1 lists the equipment parameters of the MTS biaxial test system.

Table 1. Technical parameters of equipment of MTS biaxial test system.

Load(kN)	Travel(mm)	Collet spacing(mm)	Flat collet(mm)			Temperature range	Frequency range(Hz)
			Length	Width	Thick		
±100	±100	100-300	60	45	0-7	-70- 310	0-20

The apparatus allows for in-plane biaxial tension, compression, torsion, and high and low temperature testing. Figure 3 depicts the cruciform specimens of the original specimen and the shape-optimized specimen. After the specimen was clamped, a force of 30kN is applied in both the horizontal and vertical directions, and the strain during the tensile test is measured by DIC equipment (table 2).

The strain distribution of the cruciform specimen at the intersection of the crossarms can be collected by digital image correlation (DIC) (table 2).

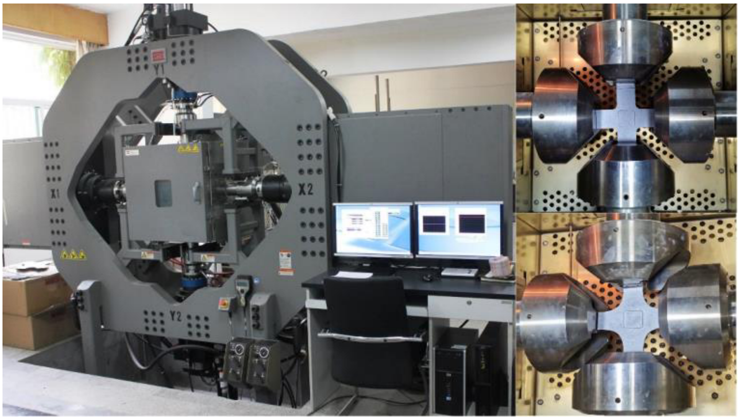


Figure 3. MTS Biaxial Test System.

Table 2. Technical parameters of equipment of DIC.

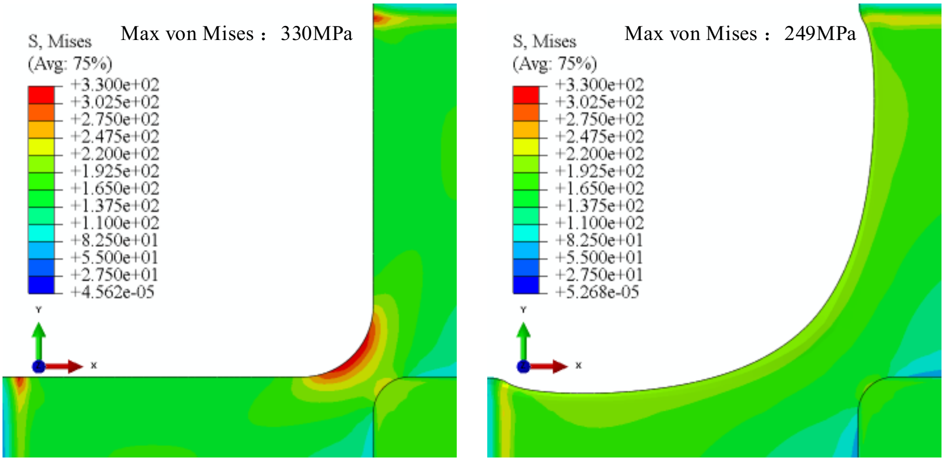
Items	Technical parameters
Measuring range (mm)	10*8 to 5000*4150
Camera type	CCD
Maximum acquisition rate	15Hz
Time of exposure	0.1ms to 2s
Strain measurement range	0.02% to >100%
Strain accuracy	0.01%
Measurement result	2D or 3D displacement, strain, and construction profile

3. Results

Based on the results of finite element simulation and experimental verification, this section explained how optimizing the boundary at the crossarm intersection, with the fitted boundary, can effectively reduce the stress concentration at the crossarm intersection.

3.1. Finite Element Simulation Results

Under the same displacement boundary conditions, the original specimen exhibits severe stress concentration at the crossarm intersection, whereas the optimized specimen exhibits uniform stress distribution along the crossarm intersection boundary. The maximum von Mises stress at the specimen's crossarm intersection decreased from 330MPa to 249MPa after shape optimization (figure 4).



(a) Unoptimizied specimen (b) Shape-optimized specimen

Figure 4. Stress distribution at crossarm intersection before and after shape optimization

3.2. Mathematical Expression of Boundary

According to the optimized shape in figure 4 (b), we finally decide to use Equation (3) to fit the boundary shape.

$$y=(a+bx)^{-1/c} \tag{3}$$

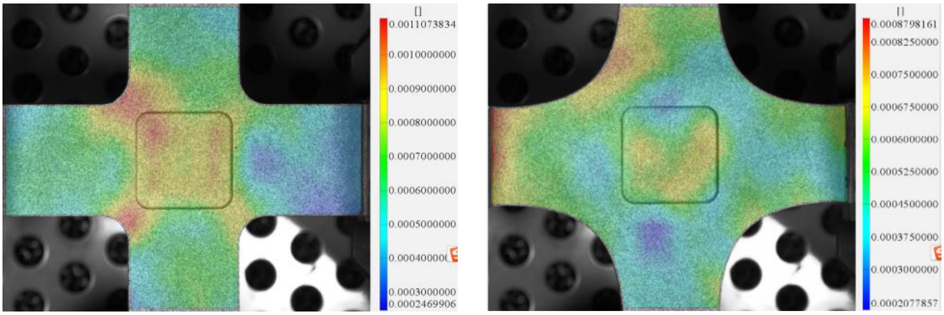
The parameters *a*, *b* and *c* in equation (3) are solved by using 31 points along the shape-optimized curve. The solution results are shown in table 3. The coefficient of determination reach 0.99.

Table 3. Fitting parameters.

	Value	Std Err	Range (95% confidence)	DOF
a	-0.000061	0.000028	-0.000119 to -0.000003	31
b	-0.00004	0.000002	-0.000007 to -0.000000	31
c	3.101030	0.151790	2.783329 to 3.418730	31

3.3. Experimental Verification

In the original specimen, there is a severe strain concentration at the crossarm intersection, while the strain concentration at the crossarm intersection of the optimized specimen has been drastically reduced. Although the strain distribution deviates from the ideal state due to the test equipment's deviations in loading coaxiality, the uniform strain distribution (figure 5(b)) corresponds to the uniform stress distribution (figure 4 (b)) at the intersection of cross arms.



(a) Original specimen (b) Shape-optimized specimen

Figure 5. Strain distribution at crossarm intersection before and after shape optimization.

4. Discussion

We found that the shape optimization algorithm based on the finite element method could effectively reduce the concentration of stress/strain at the intersection of the crossarms. The mathematical expression of the boundary shape at the crossarm intersection accurately could express the optimized boundary shape. The finite element simulation results demonstrated that the optimized specimen could effectively improve the stress distribution at the crossarm intersection; The experimental results demonstrated that the optimized specimen could effectively improve the strain distribution at the cross arm of the cruciform specimen; The coefficient of determination between the optimized shape's boundary and the mathematical expression reach 0.99. As a consequence, the finite element method is effective for improving the cross-arm intersection shape of the cruciform specimen.

In comparison to the optimization of cruciform specimens based on parameter optimization, the shape optimization algorithm could optimize the boundary of cruciform specimens more effectively since the boundary breaks through the constraints of geometric features during the optimization process. Therefore, the nonparametric optimization algorithm could optimize the boundary form of the intersection of the cruciform specimen's cross arms more effectively.

The cruciform specimen's stress concentration at the crossarm intersection is primarily influenced by its geometric structure. Therefore, although Q460, an isotropic material, was used in the simulation and test, it also applies to anisotropic materials. Although this paper focuses solely on the geometry involved in the optimization process, the mathematical expression of boundary form can be applied to other cruciform specimens. The cruciform specimen optimized for isometric tension can also achieve excellent results under varying load ratios (optimization under different load ratios can obtain optimal boundary form under specific load ratios).

To improve the stress concentration at the crossarm intersection of the cruciform specimen, the cruciform specimen's boundary is optimized using shape optimization based on the finite element method, and the mathematical expression of the optimized boundary is obtained. The numerical and experimental results indicate that the optimized specimen boundary can significantly enhance the stress/strain distribution of the cruciform specimen and decrease the stress concentration in the cross-arm transition region. This paper proposes an optimization method that can effectively improve the stress concentration at the intersection of the cruciform specimen's cross arms. It provides a reference for the structural design of the boundary shape of the cruciform specimen and a method for measuring large strain in the plane biaxial test.

5. Conclusion

An optimization method using the finite element method and shape optimization technology was developed to optimize the intersection boundary of cruciform specimen. The method can be used to effectively distribute the stresses and strains at the boundary intersections of cruciform specimens and reduce the stress concentrations at the crossarm intersections. Unlike the parametric optimization method, the nonparametric optimization method is employed to circumvent the restrictions of geometric feature parameters and locate the most optimal global solution in a plane curve. The optimized boundary is expressed by a mathematical function based on curve fitting technology, which can be used as a reference for the structural design of cruciform specimens.

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