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Design and Mechanical Properties of Flat Anchorage Limit Plate

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Abstract: To address the safety problems caused by clips being squeezed by jacks and wire slipping in the tensioning process of flat anchorages, we designed a limit plate to be used with a flat anchorage, and we studied the mechanical properties of the anchorage system after adding the limit plate through numerical simulation. Lastly, the limit plate was created and applied in a practical engineering scenario to test its safety performance. The results showed that the newly designed limit plate changed the butt position of the jack during tension, increased the hole distance, and hid the clips in the hole position of the limit plate, thus mitigating the safety hazard caused by the narrow surface tension construction in practice. The limit plate alleviated the stress concentration on the anchorage, and the extreme stress value decreased by 10–13%. Adverse effects, such as stress concentration caused by tension, were transferred to the replaceable limit plate, thus improving the reliability of the flat anchorage. The symmetrical tensioning scheme represented by sequential tensioning of holes 1, 4, 2, 5, and 3 is recommended, which produced the lowest extreme stress value of 685.55 kPa, which is 22.42 kPa lower than the maximum value of various other schemes.

Keywords: bridge engineering; flat anchorage limit plate; numerical simulation; mechanical properties

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1. Introduction

With the rapid development of national high-speed railways and expressway projects, prestressed structures have been increasingly widely used. Various new high-strength prestressed members have been designed, and various new anchorages are being widely used, among which the most important application is for various new bridges. The new 2000 MPa parallel steel wire stay cable used for the Hutong Yangtze River Bridge was specifically designed with a supporting anchorage in the research and development stage, and the stress and deformation in the anchorage were analyzed using the finite element method, the results of which verified that the strength and stiffness of the anchorage met the requirements [1]. Similarly, in the research and development of a 1960 MPa main cable steel wire and cable strand for the Humen Second Bridge, the corresponding anchorage was specifically designed, the design drawing was created, and finite element analysis was performed for verification [2]. In the construction of the Wuhan Qingshan Yangtze River Bridge, the anchorage with a 1860 MPa stay cable was specifically designed, and 42CrMo as selected as the anchorage material. The anchorage size was studied and checked using finite element analysis [3]. During the construction of the Third Yangtze River Bridge in Wuhu, a DM upsetting anchorage was used to stretch the steel wire, and a series of measurements were recorded to avoid quality problems such as fractures caused by eccentric stress at the pier head [4]. In the construction of the Wuhe Dinghuai Huaihe River Bridge, rotary cables in the same direction were adopted, a special anchorage system was designed, and specific construction technology was studied [5].

The development of special anchorages is sometimes aimed at specific materials; for example, when FRP composite materials have been used to strengthen prestressed members, many scholars have designed matching anchorages. Yang Zeying et al. [6] designed a clip-bonded anchorage with a jack to tension CFRP bars. Zhang Baojing et al. [7]

designed a set of anchorages for tensioning and strengthening CFPR plates and tested the mechanical properties of strengthened beams. Guo Rong et al. [8] designed a new anchorage for bonded prestressed CFRP plates, which were used to strengthen RC beams for a fatigue performance test. Shang Shouping et al. [9] adopted a self-developed CFRP plate tensioning anchorage device for an experimental study on the creep performance of strengthened beams on bridges, which could prevent the prestress loss caused by anchorage slip. Viktor Gribniak et al. [10] designed a frictional anchorage system for flat CFRP ribbon strips and developed an anchorage prototype optimizing the geometry for compact spiral distribution to ensure the gripping system's specific traction ratio. A new split wedge anchorage system was proposed for FRP cables by Damiani et al. [11], which has a cable capacity of 257 kN. Shakiba et al. [12] set handmade mat anchorages between concrete and GFRP bars to enhance bonding. Bernd Zwingmann et al. [13], Xiao Xinhui et al. [14,15], Deng Enfeng et al. [16], and Masoud Abedini et al. [17] also performed related studies.

After the anchorage design is completed, experimental studies of its mechanical properties are usually required. Zhong Xingu et al. [18] studied the tangential stiffness between different anchorages and backing plates through field tests and theoretical analyses. Shi Long et al. [19] designed a complete set of anchorage systems, including an anchor backing plate and a clip, to cope with the tension of 2000 MPa prestressed steel strands and performed numerical simulations and static load testing to study the anchorage's performance. In the study of long-span prestressed beamless floor slabs, Zhang Caigang et al. [20] used clip anchorage to tension prestressed tendons, described the tensioning process and key points, and optimized the design.

Many scholars have studied anchorages matched with some special materials. Du Yunxing and Tang Ziyun [21] designed a new type of inorganic adhesive-impregnated carbon fiber bundle clamp anchorage, determined the appropriate anchorage size, and tested the anchorage performance through static tensile testing. Sun Shengjiang et al. [22] designed a straight-tube bonded anchorage for composite steel bars composed of basalt fibers to test the tensile properties of the composite steel bars. Fei Hanbing et al. [23] designed a new anchorage matched with filled epoxy-coated steel strand, determined the most suitable anchorage size design through finite element simulation analysis, and conducted static load tests to verify its performance.

The above results show that researchers have extensively studied anchorages in various application scenarios, and a variety of new anchorages have been designed. At present, prestress is usually applied to a post-tensioned hollow slab beam or thin concrete structure in China by directly tensioning prestressed flat anchorages with single-hole prestress tensioning equipment, as shown in Figure 1 [24]. However, in the traditional method, because the structure of the flat anchorage is compact, and the outer edge of the clip in the hole on the anchorage is exposed outside the end face, the actual spacing of each hole is small. As such, in the butt joint process between the tension jack and the flat anchorage, the clip on the adjacent hole position of the butt joint hole and the front-end base of the jack may contact and squeeze. Sometimes, the base at the front end of the jack may even touch the adjacent steel strand, which results in the outer end of the clip on the adjacent hole position extruding and deforming, which can easily cause the sliding of the tensioned steel strand or the inclination of the tension direction of the jack, and the steel strand may even break. To avoid these problems, simply reducing the thickness or length of the front base of the jack seriously affects the use strength of the jack, causing the jack to deform during use and the wires to become slippery. If serious, the clip can fly out due to slippery wires, which poses safety risks.

Due to the use of circular limit plates in circular anchorages, the above risks do not arise during the construction process; however, owing to the structural size limitations, flat anchorages are not equipped with a better limit device. To avoid the abovementioned safety problems in the tensioning process of flat anchorages, we used the idea of a circular anchorage limit plate as a reference, designed a flat anchorage limit plate, analyzed the mechanical properties of the new type of limit device in the tensioning process with finite element software, and initially applied the proposed limit plate on a construction site. The results showed that the limit plate avoids the aforementioned safety problems, providing a solution for reducing the tension risk of flat anchorages for similar projects.

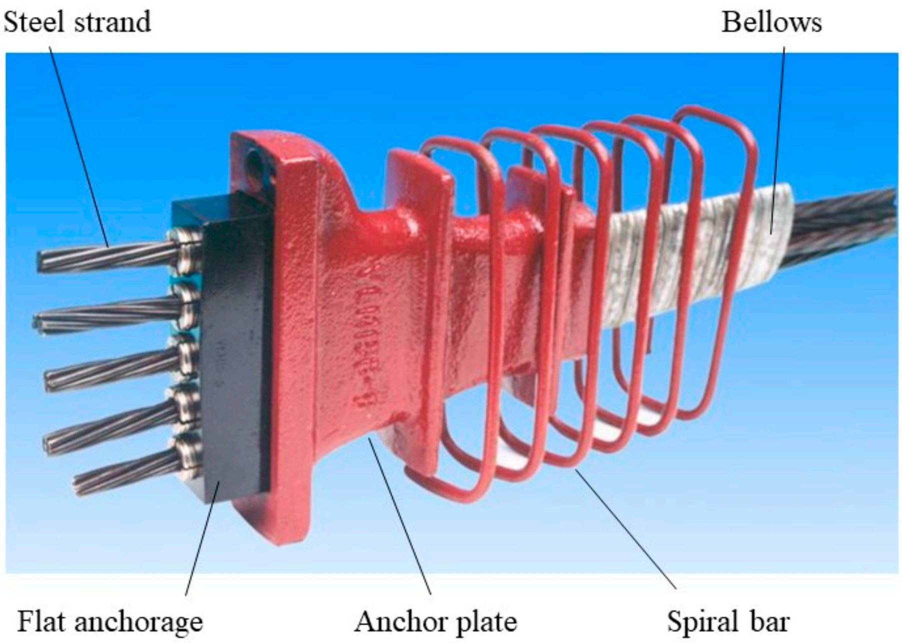


Figure 1. Flat anchorage.

2. Design of Flat Anchorage Limit Plate

2.1. Application Background of Limit Plate

During the construction of the Huainan Huaishang Huaihe River Highway Bridge, the thickness of the superstructure of the approach bridge box girder was found to be only 180 mm, as shown in Figure 2, and flat anchorages were needed for tensioning steel bars. During the construction, in the tensioning process of flat anchorages, safety problems such as sliding wire and squeezing deformation of clips by the jack, as mentioned in Section 1, can easily occur. The main reasons for these problems were mentioned earlier: the small hole spacing and lack of limiting devices.

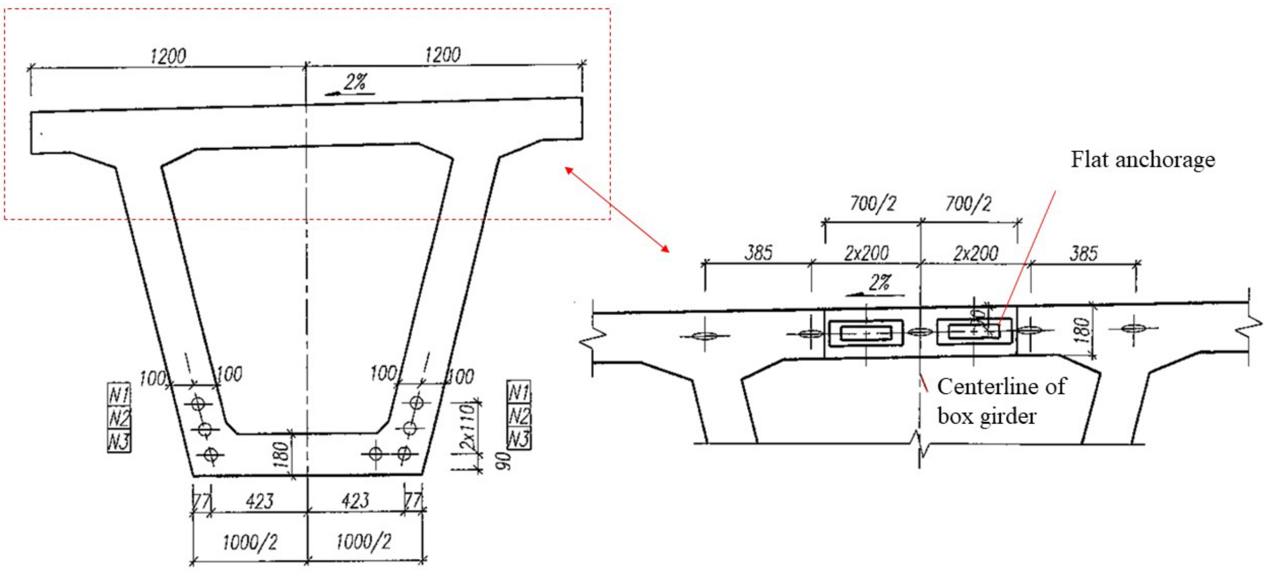


Figure 2. Flat anchorage position (unit: mm).

To solve this problem on site, the team members designed a limit plate for a flat anchorage to increase the hole spacing during loading, prevent squeezing and touching, and limit the clip.

2.2. Limit Plate Design

This design is aimed at the commonly used types of clips, steel strands, and five-hole flat anchorages on the market, to ensure that they can be widely used on construction sites. To be suitable for narrow and weak concrete tensioning, the overall dimension of the limit plate should be kept close to that of the five-hole flat anchorage.

Figure 3 depicts the structure of a limit plate with two limit holes. The aperture of the first limit hole should be larger than the diameter of the steel strand and smaller than the diameter of the back end of the clip. The depth of the second limit hole should be compatible with the retraction of the clip. The depth setting range is 6.5–8 mm, and the total depth setting range of the limit plate is 30–60 mm.

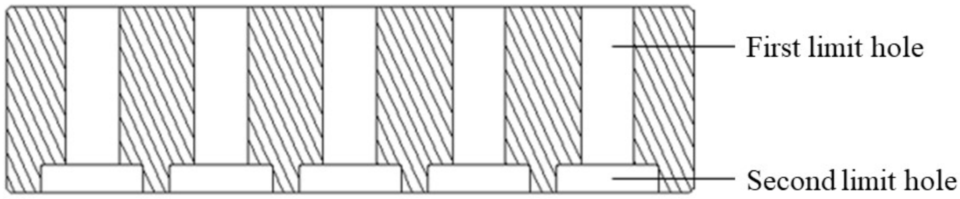


Figure 3. Limit plate structure.

The new flat anchorage system was designed to allow the addition of a limit plate at the front end of the common flat anchorage to form the structure shown in Figure 4. The limit plate is aligned with the conical hole of the flat anchorage, and the step hole scheme with a small front hole and a large back hole is adopted to ensure that the aperture of the large hole next to the conical hole is larger than the diameter of the back end of the clip. The aperture of the small hole at the other end is larger than the diameter of the steel strand and smaller than the diameter of the back end of the clip. The depth of the big hole is compatible with the retraction depth of the clip.

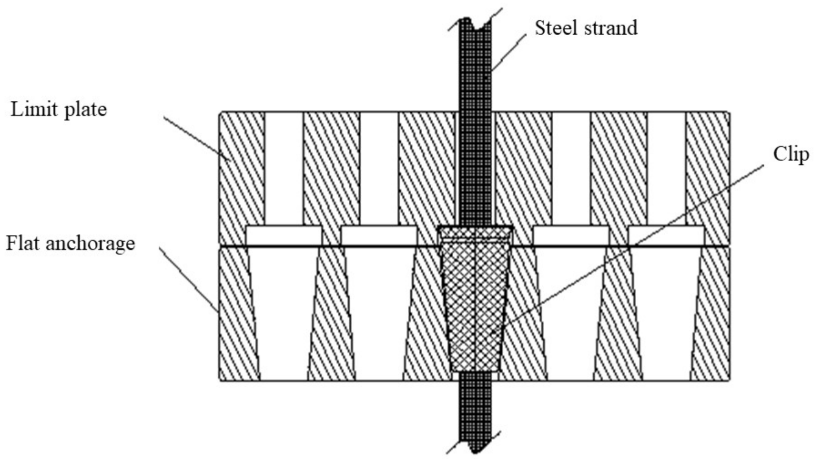


Figure 4. New flat anchorage system.

At this point in the tensioning process, the jack is no longer directly butted with the working flat anchorage but is butted with the limit plate at the front end; the hole spacing of the butt face with the jack is effectively increased. Therefore, the problem of the base at the front end of the jack contacting and extruding to the clip cannot occur, and the steel strand protruding from the adjacent hole cannot be easily contacted, which effectively avoids issues such as sliding wire, broken steel strand, extrusion deformation of the outer end of the clip, inclination of the tension direction of the jack, and deformation of the jack during use. In addition, because the aperture of the large hole on the limit plate is larger than the diameter of the rear end of the clip and the depth of the large hole can be matched with the retraction amount of the clip, the rear end of the clip can be fully stored in the large hole; hence, after the tension is finished, the clip has sufficient retraction space and meets the normal retraction amount requirements of the clip.

3. Establishment of Numerical Model of Flat Anchorage

According to the flat anchorage limit plate described in the previous section, a numerical analysis model was established using ANSYS finite element software, and the hexahedron element in the solid element was adopted. The model included a flat anchorage, a clip, a steel strand, and the newly designed limit plate, as shown in Figure 5. The conventional flat anchorage model without a limit plate for a comparative study is also shown in Figure 5a. Figure 5b shows the combined model of the limit plate and flat anchorage, Figure 5c shows a model of the clip, Figure 5d shows the steel strand model, and Figure 5e shows the limit plate model. As the main component materials involved were all steel, the structural steel simulation in the material library was directly selected in the software, and the elastic model was selected as the constitutive model. The material parameters involved in the numerical simulation are detailed in Table 1.

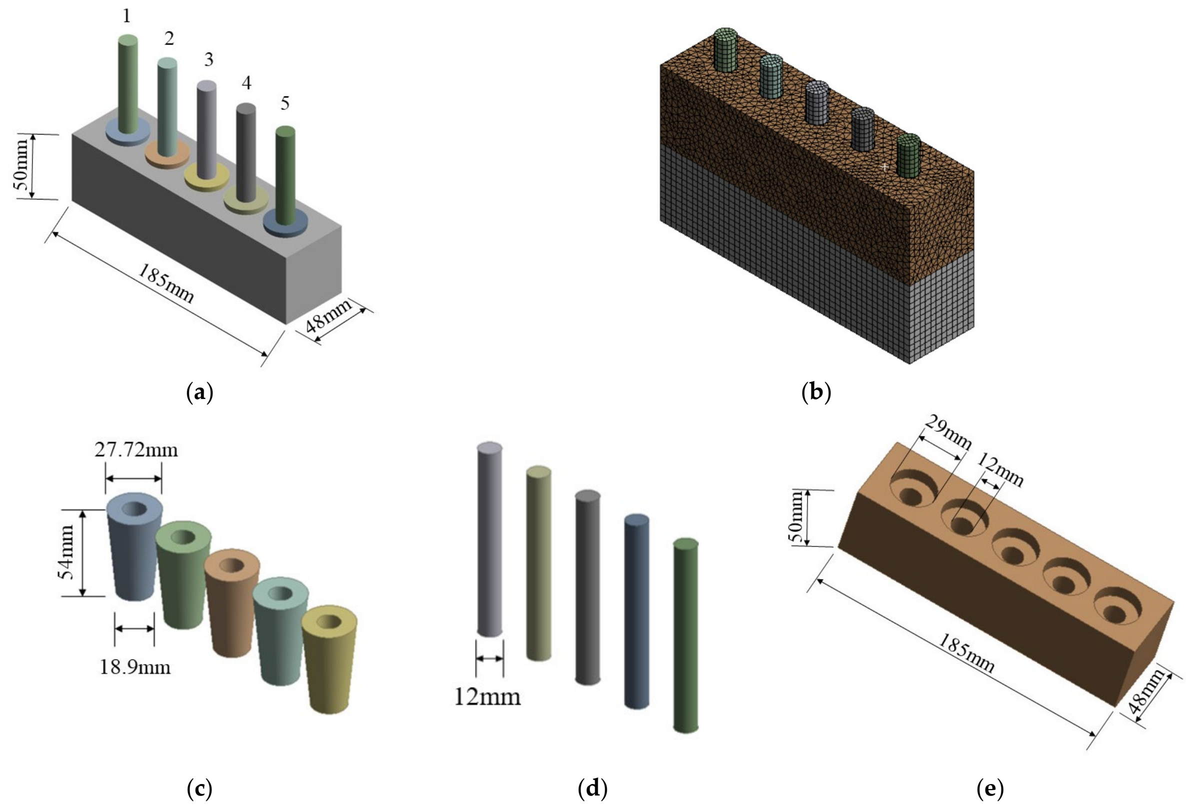


Figure 5. Numerical model: (**a**) conventional flat anchorage (numbers 1-5 represent the number of holes), (**b**) new flat anchor system, (**c**) clip, (**d**) steel strand, and (**e**) limit plate.

Table 1. Material parameters.

Component	Elastic Modulus (MPa)	Density (kg·m^{-3})	Poisson's Ratio	Compressive Yield Strength (MPa)
steel strand/clip/flat anchorage/limit plate	2×10^5	7850	0.3	250

The model dimensions were as follows: the outer contour size of the flat anchorage was 185 mm (length) × 48 mm (width) × 50 mm (height), the diameter of the bottom hole was 18 mm, the diameter of the top taper hole was 27 mm, the taper of the hole was 14°, the center distance between holes was 34 mm, and the edge of the side hole was 24.5 mm away from the short side of anchorage and 10.5 mm away from the long sides of both sides. The diameter of the steel strand was 12 mm, the height of the clip was 54 mm, the diameter of the bottom was 18.9 mm, and that of the top is 27.72 mm. The length and width of the limit plate were the same as that of the flat anchorage, with a height of 50 mm; the bottom cylindrical hole had a diameter of 12 mm, and the upper cylindrical hole had a diameter of 29 mm and a depth of 8 mm.

The boundary conditions and internal contact settings of the model were as follows: the bottom surface of the flat anchorage was arranged as a fixed support; the contact surface between the top surface of the flat anchorage and the bottom of the limit plate was arranged to be only supported by compression; friction contact was arranged between the clip and the steel strand and between the clip and the anchorage. No contact occurred between the limit plate and the steel strand.

4. Mechanical Properties of Flat Anchorage Limit Plate

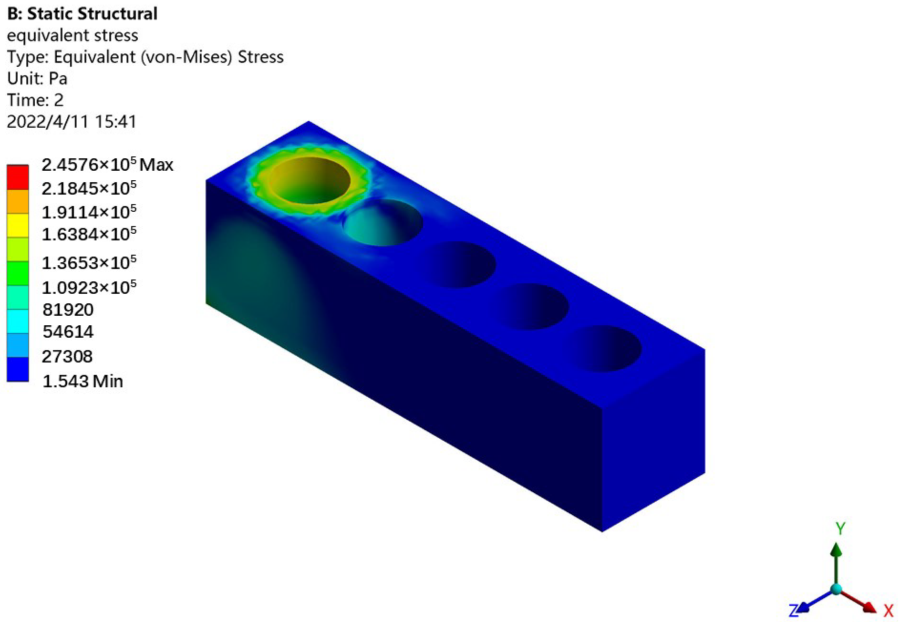
Using the numerical model established in Section 3, prestress was applied to the conventional flat anchor system and the newly designed flat anchor system, and the differences in the stress distribution of the flat anchorage in different tensioning stages were analyzed after adopting the new limit plate.

4.1. Tensile Stress Distribution of Single Hole

According to the numbering in Figure 5, single-hole tension was separately applied to holes 1, 2, and 3, with a tension tonnage of 20 t, i.e., a tension force of 196 kN. Figure 6 shows the stress distribution of the flat anchorage under the two conditions. The figure shows that, after using the limit plate, the stress concentration on the flat anchorage was alleviated, and the extreme stress value decreased from 245.76 kPa to 219.43 kPa, representing a decrease of 10.7%. This also occurred in the tension of holes 2 and 3 alone. The extreme stress values are shown in Table 2, showing more notable decreases of 45.9% and 48.3%, respectively. The stress relaxation of hole 3 in the middle was the most remarkable. We found that the tension force is shared by the newly added limit plate, which is a replaceable member, whereas the flat anchorage is a permanent member; hence, the adverse effects of the tension force can be passed on to the replaceable limit plate, thus improving the reliability of the flat anchorage. We calculated the standard deviation of the extreme stress value of a conventional flat anchorage as 19.02 kPa and that of new flat anchorage system as 60.86 kPa. The limit plate had differing effects on the tension results of the different hole positions.

4.2. Tensile Stress Distribution of Double Holes

After the first hole stretches, the second hole stretches, and many different stretching schemes may arise. Figure 7 shows the stress distribution results of the second hole of the flat anchorage stretching after the first hole stretched. Similarly, with the limit plate, the stress concentration of the flat anchorage stretched on the second hole was substantially alleviated, and the extreme stress value dropped from 519.08 kPa to 485.89 kPa, representing a decrease of 6.4%. Different combinations of tension holes and their corresponding stress extreme results are detailed in Table 3. The above results correspond to tension holes 1 and 2 in Table 3, which means that hole 1 tensioned first, followed by hole 2. The table shows that, overall, the drop in the stress extreme value when the second hole was tensioned was not as large as that when the first hole was tensioned, and the maximum stress results for the different schemes differed little. Relatively, the drop in the extreme stress value was larger when the third hole was tensioned in the first two steps. We calculated the standard deviation of the stress extreme value of the conventional flat anchorage as 5.09 kPa and that of the new flat anchorage system as 7.20 kPa. The influence of the limit plate on the tension results of the different double holes was weak.



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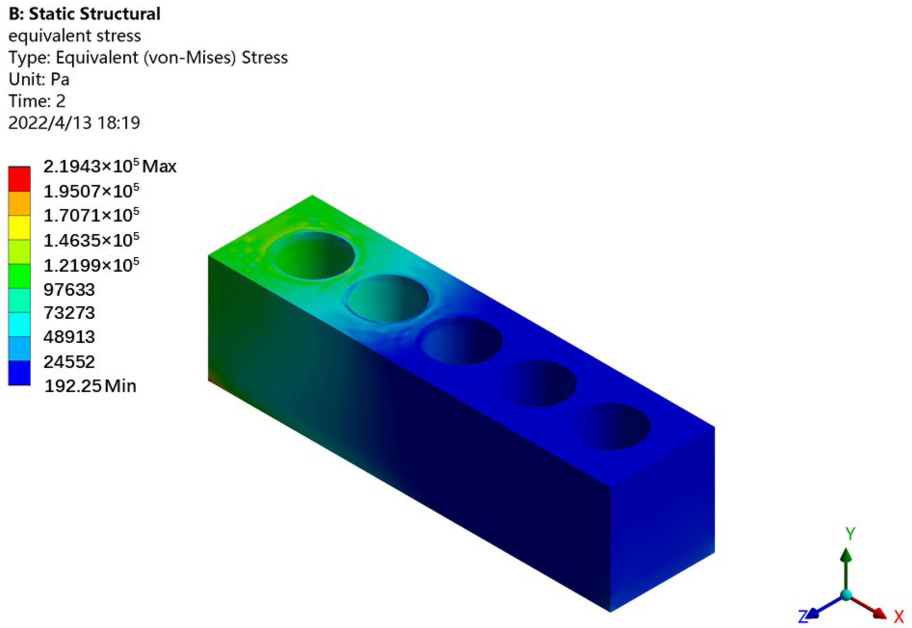

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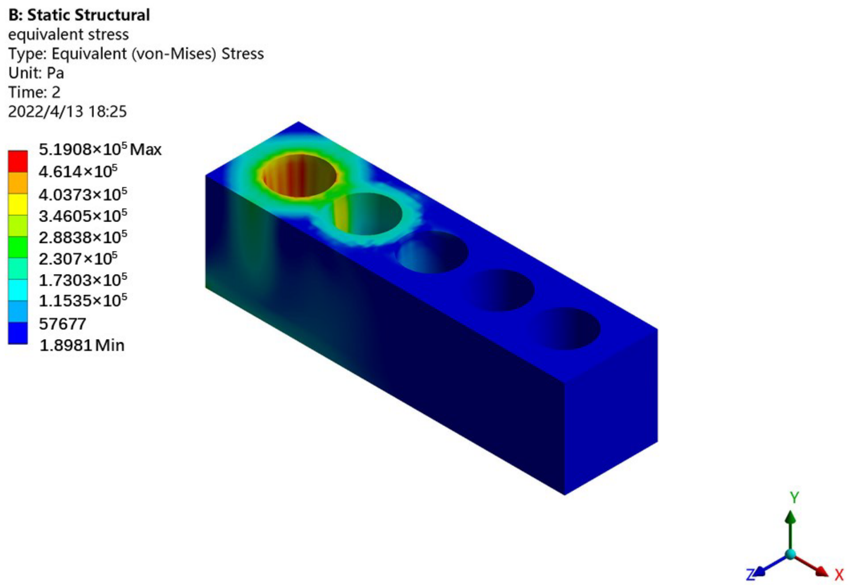
Figure 6. Tensile stress distribution of hole 1: (**a**) conventional flat anchorage, and (**b**) anchorage of new flat anchor system.

Table 2. Extreme value of single-hole tensile stress.

Tension Hole Position	Maximum Equivalent Stress of Conventional Flat Anchorage (kPa)	Maximum Equivalent Stress of Anchorage in New Flat Anchor System (kPa)	Decrease (%)
1	245.76	219.43	10.7
2	225.74	122.07	45.9
3	207.73	107.49	48.3



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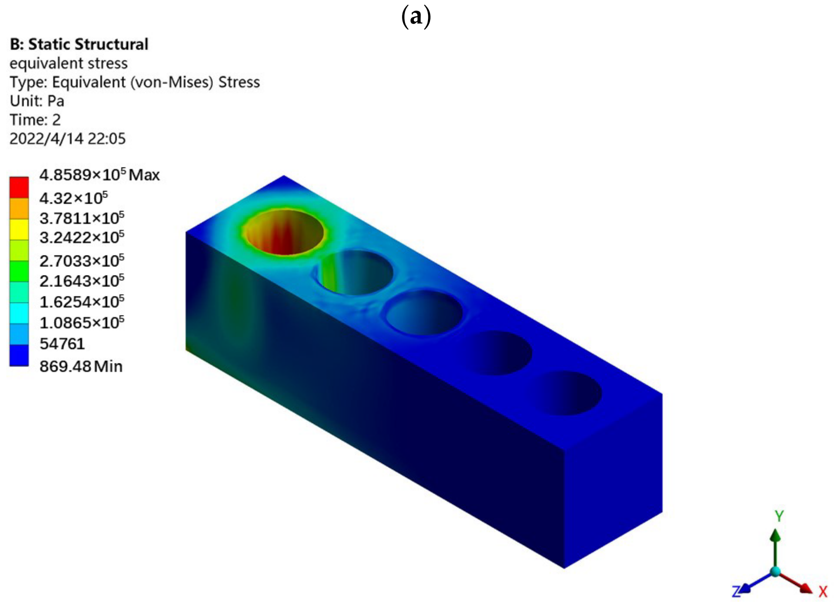

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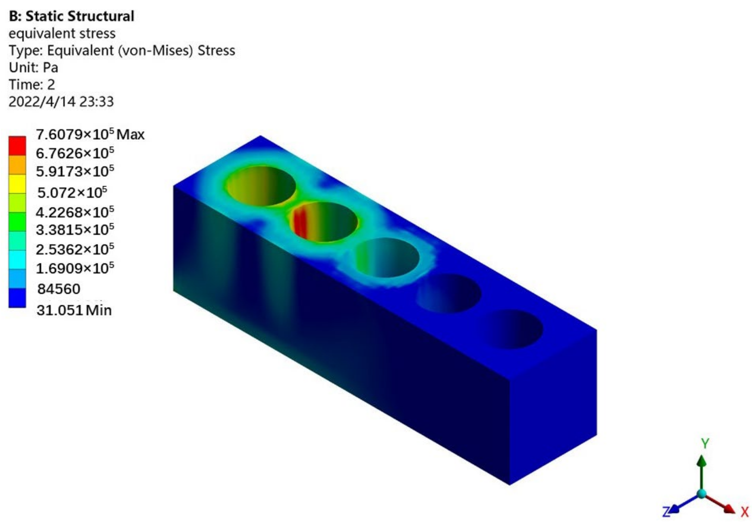
Figure 7. Tensile stress distribution of holes 1 and 2: (**a**) conventional flat anchorage, and (**b**) anchorage of new flat anchor system.

Table 3. Extreme value of double-hole tensile stress.

Tension Hole Position	Maximum Equivalent Stress of Conventional Flat Anchorage (kPa)	Maximum Equivalent Stress of Anchorage in New Flat Anchor System (kPa)	Decrease (%)
1 and 2	519.08	485.89	6.4
1 and 3	514.86	474.47	7.8
1 and 4	514.52	481.88	6.3
1 and 5	514.80	487.09	5.4
2 and 1	525.66	495.84	5.7
2 and 3	527.76	487.73	7.6
2 and 4	524.65	488.59	6.9
2 and 5	525.49	497.08	5.4
3 and 1	520.98	476.80	8.5
3 and 2	524.32	487.57	7.0

4.3. Three-Hole Tensile Stress Distribution

After tensioning two holes, when tensioning the third hole, more tensioning combinations were produced. Figure 8 shows the simulation results after tensioning holes 1 and 2 and then tensioning hole 3. Table 4 shows the stress extremes under different combinations. In the first row of the table, 1, 2, and 3 correspond to those in Figure 8. Table 4 shows the working condition combinations of the conventional flat anchorage in the high-stress state. After using the limit plate, the extreme stress value markedly dropped. For example, when holes 1, 2, and 3 were stretched in the above sequence, the extreme stress value dropped from 760.79 kPa to 675.88 kPa, representing a decrease of 11.2%. Figure 8 also shows that, after adding the limit plate, the stress around hole 3 substantially decreased. In addition, the sequential tension of holes 1, 5, and 3 is the best combination of working conditions, and the differences in the stress extreme before and after adding the limit plate were the smallest, while the decline was also higher in low-stress working conditions, reaching 7.7%, with the limit plate playing a substantial role. The standard deviation of the extreme stress value of the conventional flat anchorage was 116.62 kPa, whereas that of the new flat anchorage system was 91.16 kPa. The limit plate reduced the dispersion of the three-hole tension results, with large differences among the different schemes.



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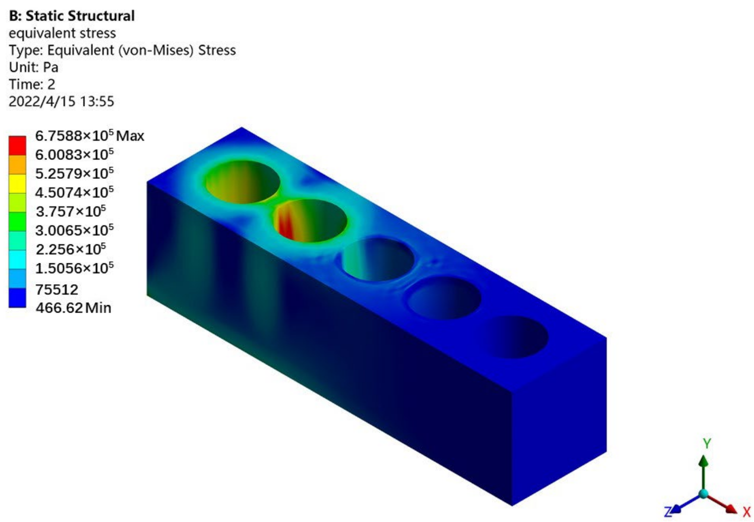

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Figure 8. Tensile stress distribution of holes 1–3: (**a**) conventional flat anchorage, and (**b**) anchorage of new flat anchor system.

Table 4. Extreme value of three-hole tensile stress.

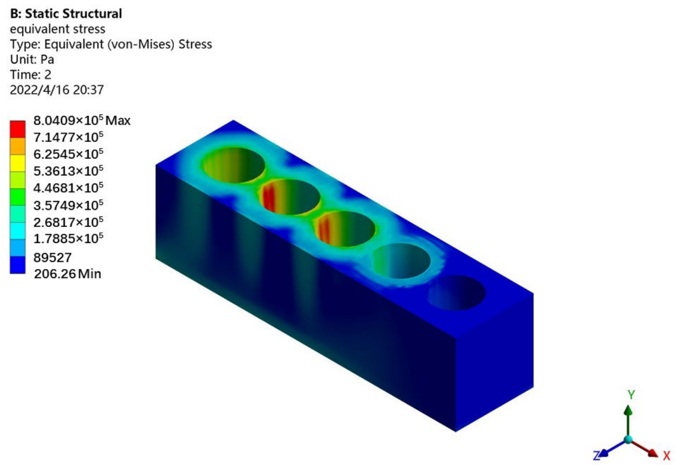
Tension Hole Position	Maximum Equivalent Stress of Conventional Flat Anchorage (kPa)	Maximum Equivalent Stress of Anchorage in New Flat Anchor System (kPa)	Decrease (%)
1, 2, and 3	760.79	675.88	11.2
1, 2, and 4	755.70	668.45	11.5
1, 2, and 5	756.93	663.29	12.4
1, 3, and 2	526.69	487.43	7.5
1, 3, and 4	526.77	487.77	7.4
1, 3, and 5	523.34	484.3	7.5
1, 4, and 2	518.60	484.41	6.6
1, 4, and 3	521.54	482.28	7.5
1, 4, and 5	520.73	490.83	5.7
1, 5, and 2	519.33	484.76	6.7
1, 5, and 3	515.10	475.61	7.7
1, 5, and 4	764.04	679.05	11.1
2, 3, and 4	761.01	673.81	11.5
2, 3, and 5	761.64	668.58	12.2
2, 4, and 1	529.08	495.23	6.4
2, 4, and 3	529.53	488.77	7.7
2, 4, and 5	526.97	493.03	6.4

4.4. Four-Hole Tensile Stress Distribution

After three holes were stretched, when the fourth hole was stretched, more working condition combinations were created. Figure 9 shows the simulation results of stretching the fourth hole after stretching holes 1, 2, and 3. Table 5 shows the stress extreme results under each working condition. The stress relaxation around the anchorage hole is clearly shown in the figure, and the extreme value of anchorage stress in the figure dropped from 804.09 kPa to 703.72 kPa, representing a decrease of 12.48%. A comparison of the data in the table shows that, as in Section 4.3, the combination of the working conditions in the high-stress state had different effects. When holes 1, 3, and 5 were stretched and hole 2 or 4 was stretched, the stress extreme was small, and the limit plate played a certain role in relieving stress. This was the optimal combination of working conditions. The standard deviation of the stress extreme of the conventional flat anchorage was 81.29 kPa, and that of the new flat anchorage system was 63.25 kPa. The limit plate reduced the dispersion of the tension results for four holes, and the differences between the different schemes were lower than observed with three holes.

4.5. Five-Hole Tensile Stress Distribution

When tensioning the fifth hole, only five situations were considered, i.e., with the last tensioning hole a hole 1, 2, 3, 4, or 5, as shown in Table 6. Figure 10 depicts the simulation results for tensioning the fifth hole. Combined with the data in Table 6, we found that the extreme stress of the anchorage dropped by 12.83%, showing that the proposed system still played an important role in relieving stress concentration. By comparing the five working conditions, we found that, when the holes on both sides of hole 3 were symmetrically stretched first and then hole 3 was stretched, the extreme anchorage stress value was the smallest in both cases. According to the results in Sections 4.1–4.4, the symmetrical tensioning scheme represented by the sequential tensioning of holes 1, 4, 2, 5, and 3 should be adopted in tensioning, which not only ensures that the anchorage stress is not too large in the tensioning process but also results in a smaller final stress extreme value. The standard deviation of the stress extreme of the conventional flat anchorage was 18.63 kPa, and that of the new flat anchorage system was 8.37 kPa. The limit plate reduced the dispersion of five-hole tension results, and the differences between the different schemes were small.



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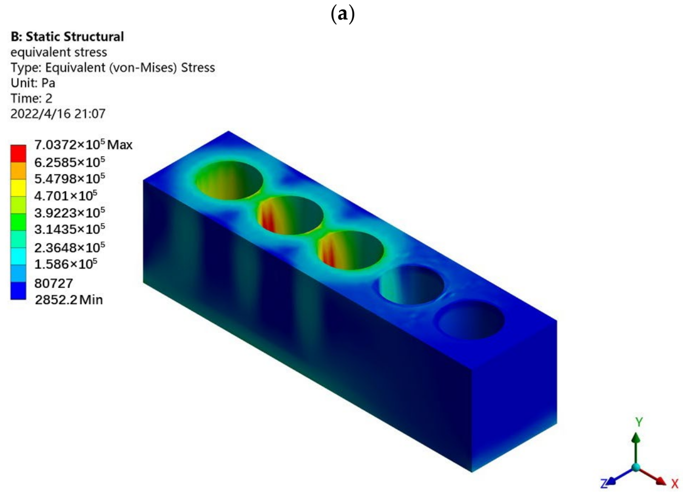

(**b**)

Figure 9. Tensile stress distribution of holes 1–4: (**a**) conventional flat anchorage, and (**b**) anchorage of new flat anchor system.

Table 5. Extreme value of four-hole tensile stress.

Tension Hole Position	Maximum Equivalent Stress of Conventional Flat Anchorage (kPa)	Maximum Equivalent Stress of Anchorage in New Flat Anchor System (kPa)	Decrease (%)
1, 2, 3, and 4	804.09	703.72	12.48
1, 2, 3, and 5	804.71	697.85	13.28
1, 2, 4, and 3	754.95	676.92	10.34
1, 2, 4, and 5	754.34	664.28	11.94
1, 2, 5, and 3	761.88	676.04	11.27
1, 2, 5, and 4	756.78	668.63	11.65
1, 3, 4, and 2	761.64	677.83	11.00
1, 3, 4, and 5	764.71	683.02	10.68
1, 3, 5, and 2	523.65	486.64	7.07
1, 3, 5, and 4	523.51	487.93	6.80
1, 4, 5, and 2	763.18	677.5	11.23
1, 4, 5, and 3	768.29	684.74	10.87
2, 3, 4, and 1	798.3	695.74	12.85
2, 3, 5, and 1	763.26	678.63	11.09
2, 3, 5, and 4	760.24	673.44	11.42
2, 4, 5, and 1	757.41	673.03	11.14
2, 4, 5, and 3	761.27	685.61	9.94
3, 4, 5, and 1	808.76	702.61	13.13
3, 4, 5, and 2	807.52	708.55	12.26

Table 6. Extreme value of five-hole tensile stress.

Tension Hole Position	Maximum Equivalent Stress of Conventional Flat Anchorage (kPa)	Maximum Equivalent Stress of Anchorage in New Flat Anchor System (kPa)	Decrease (%)
2, 3, 4, 5, and 1	802.84	699.87	12.83
1, 3, 4, 5, and 2	808.61	707.97	12.45
1, 2, 4, 5, and 3	762.37	685.55	10.08
1, 2, 3, 5, and 4	803.31	703.15	12.47
1, 2, 3, 4, and 5	797.87	698.15	12.50

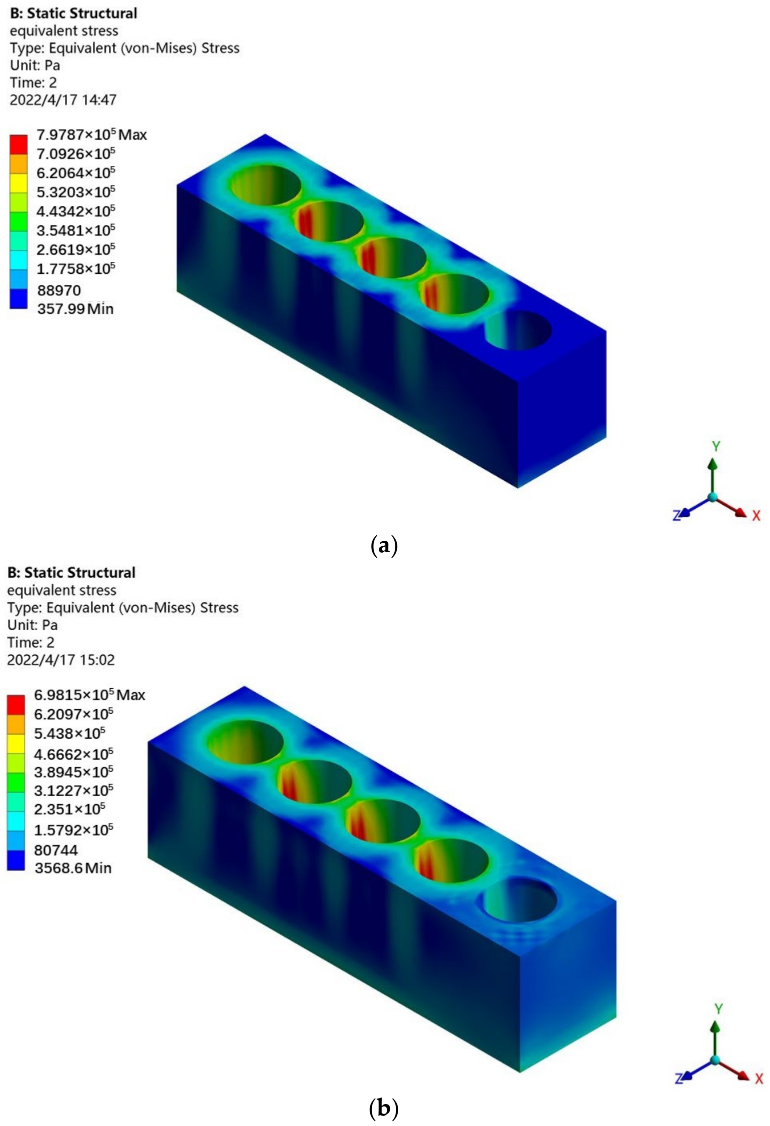

Figure 10. Tensile stress distribution of holes 1–5: (**a**) conventional flat anchorage, and (**b**) anchorage of new flat anchor system.

Figure 11 further shows the development curves of the extreme stress values of several tensioning sequences, with the corresponding numbers in the curves denoting the tensioning sequences. For example, "14253" denotes the sequential tensioning of the steel strands of holes 1, 4, 2, 5, and 3. As shown in the figure, different tensioning sequences showed gentle stress development; however, the periods of gentle change slightly differed. Regardless of the curve, the final values did not widely differ. Throughout the process, the stress extremes of the two schemes of the final tensioning of hole 3 were small, with a final stress extreme of 685.55 kPa, representing a 22.42 kPa difference from the scheme with the largest stress extremes. The stress curves were located below those of the other schemes, indicating the preferred tensioning sequence, as mentioned in the aforementioned data analysis.

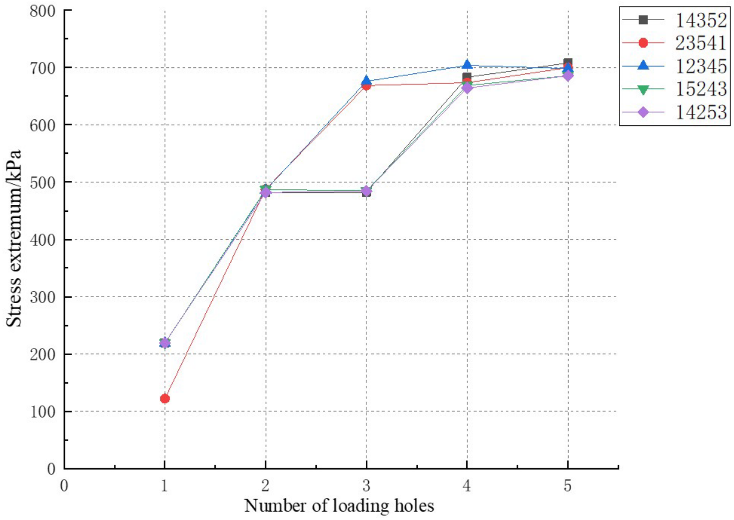

Figure 11. Stress extreme development curve.

5. Construction Site Application

On the basis of previous design and research, a batch of flat anchorage limit plates were manufactured using 45# steel, as shown in Figure 12a. For the dimensions, we referred to the flat anchorage design; the dimensions were basically consistent with those mentioned in the numerical simulation. As shown in Figure 12b, the extended clip was placed in the second limit hole of the limit plate, and the steel strand passed through the first limit hole, finally forming the shape shown in Figure 12c. As such, the limit plate adequately protected the flat anchorage, the top surface was a plane, no clips were protruding, the hole spacing increased, and the jack tension construction was convenient.

(**a**) (**b**) (**c**)

Figure 12. Physical object of limit plate: (**a**) limit plate, (**b**) limit plate installation, and (**c**) form after installation.

The device was used in the construction of narrow areas of the Huainan Huaishang Huaihe River Highway Bridge and Chizhou Yangtze River Bridge. The use position is as described in Section 2.1, mainly as the upper plate structure of the bridge box girder. Figure 13a,b show the construction site where workers used the new flat anchorage limit plate for tensioning, and the member next to the jack in the figure is the limit plate. After the application of the newly designed limit plate, no safety problems occurred at the construction site, such as sliding wires or squeezing deformation of clip by jack, and the construction efficiency was increased, which verified the feasibility of the design. Because of the low cost of the limit plate, this technology is convenient for popular use.

(**a**) (**b**)

Figure 13. Application at construction site: (**a**) jack installation, and (**b**) tensioning operation.

6. Conclusions

(1) A limit plate for use with flat anchorages was designed, which changes the jack tension work into a butt limit plate, increases the hole distance, and protects the clips. In field practice, the plate prevents safety hazards such as slippery wires and clips being squeezed and deformed by jacks, as well as increases the tension efficiency.

(2) Through numerical simulation, we found that the stress concentration of flat anchorages in the tensioning process was effectively alleviated using the limit plate, and the extreme stress value decreased by 10–13%. Because the limit plate is a replaceable member and the flat anchorage is a permanent member, the adverse effects of tensioning force are passed on to the replaceable limit plate, thus improving the reliability of flat anchorages.

(3) By simulating the five-hole tensioning process, we found that the ultimate extreme stress value of the anchorage differed little under different tensioning sequences, and the standard deviation of the extreme stress value after adding the limit plate was only 8.37 kPa. The symmetrical tensioning scheme represented by the sequence tensioning of holes 1, 4, 2, 5, and 3 should be adopted, as the ultimate stress extreme was the smallest at 685.55 kPa, being 22.42 kPa lower than the maximum value in other various schemes.

At present, although a numerical simulation was conducted on the proposed prestressed tensioning flat anchorage system including a limit plate, we found that it could effectively alleviate the stress concentration in the tensioning construction process, and we confirmed that the new flat anchorage system can avoid safety hazards such as sliding wires and clip deformation through a field application. However, more systematic research needs to be conducted, mainly including the determination of the stress and strain of the limit plate in the actual tensioning process, the manufacturing materials of the limit plate, and a sensitivity analysis of the design parameters, to verify and improve the safety of the limit plate.

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