CHAPTER 4
ROOF STRESS DURING ENTRY DEVELOPMENT

4.1 General Consideration

In underground coal mines, generally there are 3 types of entry development systems being used in longwall mining, 2-entry development, 3-entry development, and 4-entry development system. The 3-entry development system is more and more widely used because it is the minimum number of entries required for developing the panel entries by law. Therefore, the stress distributions in entry roof in the 3-entry development system are studied. But, the yield pillar system is not considered in this study.

A typical geological column is shown in Fig. 3-1. There are two types of immediate roof, the weak roof and the medium roof. The rock properties are listed in Table 4-1. The models are shown in Fig. 4-1. In this chapter, the stress distributions in the weak roof have been mainly studied. In the models, the entry width is 18 ft and the pillars are 80 ft wide and 100 ft long. The simulated floor thickness is 50 ft and the simulated mining height is 7 ft. The total model height is 107 ft. The minimum size of elements in the area of interest is 2x1.5x2 ft. The total number of the elements ranges from 25,000 to 32,000.

Based on the initial study, it is found that the overburden effects on the Von-Mises stress distributions in the immediate roof is not significant under high horizontal stress although the tensile stress increases with the overburden depth. Therefore, the stress distributions in the immediate roof will mainly be studied when the simulated overburden is 800 ft, considering a common case in the Pittsburgh seam.

As analyzed in the previous chapter, the roof properties have an effect on the stress in the immediate roof. The stress in the medium roof is larger than that in the weak roof. However, the patterns of the stress distributions are the same. Since roof failure mainly occurs in weak roof, the stress distributions in the weak roof are analyzed.

The stress angle between the orientation of the maximum horizontal stress and the entry development direction is an important factor which affects the stress distributions in the roof. It ranges from 0^0 to 90^0.

The stress ratio of the maximum to the minimum horizontal stresses also influences the stress in the immediate roof. In the initial study, the ratio ranged from 1.2 to 2.0. Since the field measurements confirm that the ratio reaches over 3.0 in some areas, in this section, the ratio ranges from 1.0 to 3.0.

In this chapter, first the stress distributions in the roof are discussed when no horizontal stresses exist. Then the stress distributions are analyzed when high horizontal stresses occur.

Table 4-1 Rock Properties Used in The Study (Fig. 3-1, p.23)

	Rock Type	Young's Modulus (x 10^6 psi)	Poisson's Ratio	Uniaxial Comp. Strength (psi)	Cohesion (psi)	Friction Angle (^{0})
Main Roof	Siltstone	2.1	0.21	6,500	1,350	25
	Shale	1.5	0.22	5,500	1,200	28
	Shale with sandstone	1.68	0.22	5,200	1,630	30
Immed. Roof	Weak shale	0.55	0.25	3,500	1,000	32
	Medium Shale	1.5	0.22	5,500	1,200	28
Seam	Coal	0.35	0.30	1,200	900	35
Immed. Floor	Shale	1.5	0.22	5,500	1,200	26
Main Floor	Claystone	1.1	0.30	1,300	760	35
	Shale with sandstone	1.68	0.22	5,200	1,630	30

Since underground observations have confirmed that there are two common types of roof failure, tensile failure and shear failure, the stresses determined from the models are: (1) the Von-Mises stress, (2) the minimum principal stress, and (3) the maximum principal stress. The Von Mises stress is one of the shear stresses contributing to the roof failure. The minimum principal stress may cause the tensile failure in the roof, and the maximum principal stress represent the combined effects of vertical and horizontal stresses. In addition, in all figures representing stress distributions in the following, a negative value denotes tensile stress and a positive one is for compressive stress.

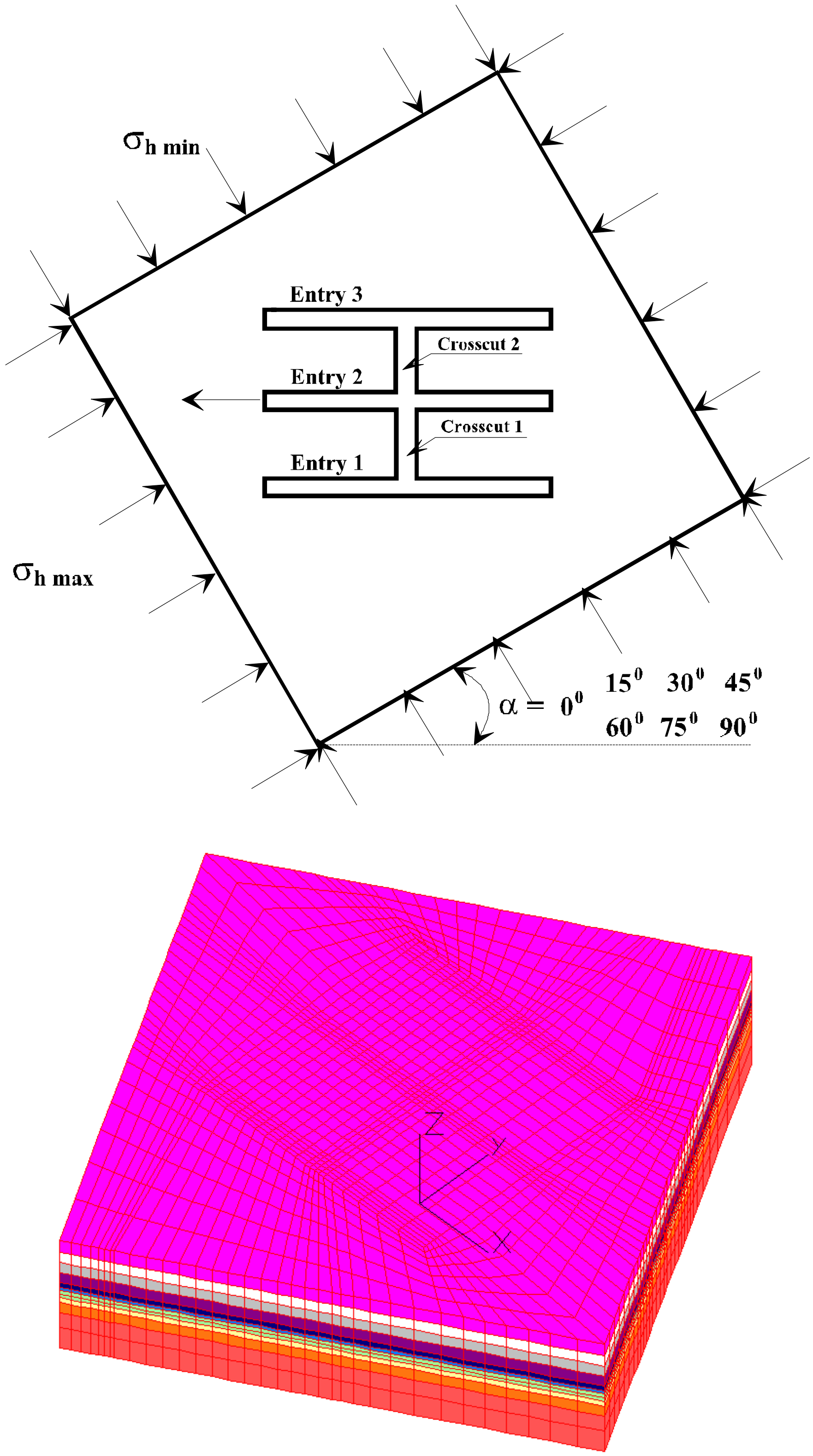


Fig. 4-1 Plan View and the Mesh of the 3-D Models for Entry development

4.2 Roof Stress without Horizontal Stress

In order to study the horizontal stress effect on entry roof, the stress distributions in the immediate roof of a longwall entry roof without horizontal stress are analyzed first. Through the analysis, the patterns of stress in the roof can be found. Then, in the following section, the stress distributions in the entry roof with horizontal stress will be studied. Through the comparison of these two cases, it can be found that the horizontal stress does have a significant effect on the entry roof.

When a 3-entry system is only subjected to the gravitation, the stress distributions in the immediate roof are shown in Figs. 4-2~4-4. In these figures, a positive value denotes compressive stress while a negative one is for tensile stress. In addition, the unit of the stress is psi.

4.2.1 Von-Mises Stress in the Roof

Figure 4-2 shows the Von Mises stress contours in the entry roofs. It indicates that the Mises stresses in these three entries' roofs are similar to each other, except that the stresses are slightly larger at the two corners of Entry 2 near to the intersection between entry and crosscut (see Fig. 4-1). In the roofs, the maximum stresses occur near the pillar ribs and the corner of the intersections, not in the middle span of the roof. If roof failure follows the Mises criterion, the roof may yield first at the corners of the intersections and along the pillar ribs.

4.2.2 Max. and Min. Principal Stress in the Roof

The maximum principal stress distributions in immediate roof are shown in Fig. 4-3. The distributions are symmetrical. Near the pillar ribs, the stresses are larger than those in the middle of entry. The minimum principal stress is shown in Fig. 4-4, which indicates that the mostly part of the immediate roof is in tension, especially in the entry center. In the central area of the roof, the tensile stress is over 300 psi while the maximum principal stress is about 50 psi. Therefore, from the tension point of view, the roof may yield in the center firstly.

Based on the above analysis, the stress distributions in the immediate roof of a longwall entry without horizontal stress have the following characters:

(1) The stress in the roof distributes symmetrically, and the stresses in the three entry roofs are the same.

(2) Near the pillar ribs and the corners of the pillar, the Von-Mises stress and the maximum principal stress reach the maximum. This indicates that cutter roof failure may occur without horizontal stress.

(3) At the center of the roof, tensile stress occurs. At the center, since the maximum principal stress is very small, the roof is subjected to tensile loading. A tensile failure may happen in the center of the entry.

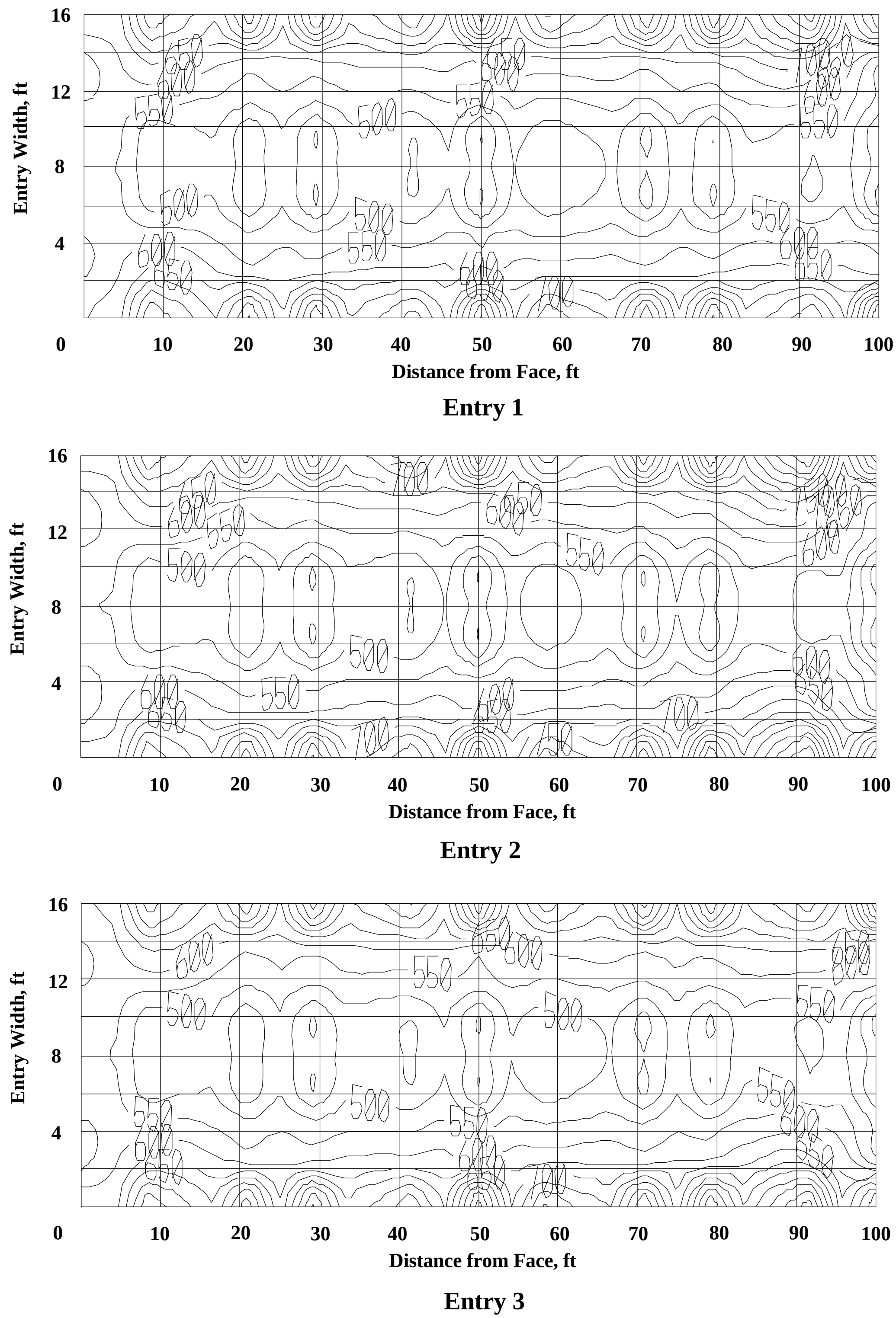
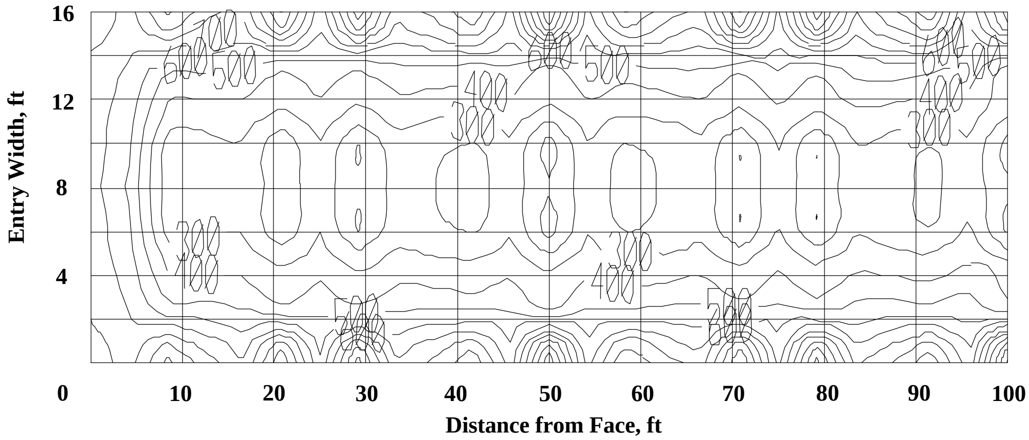
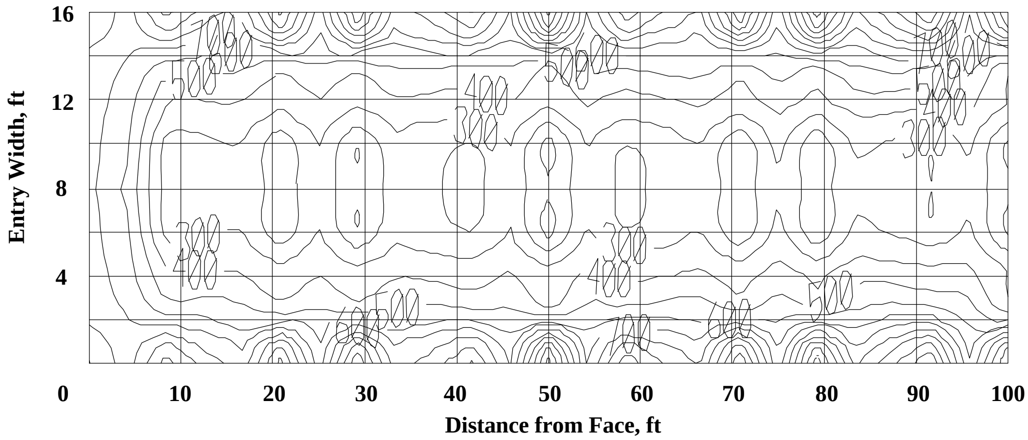


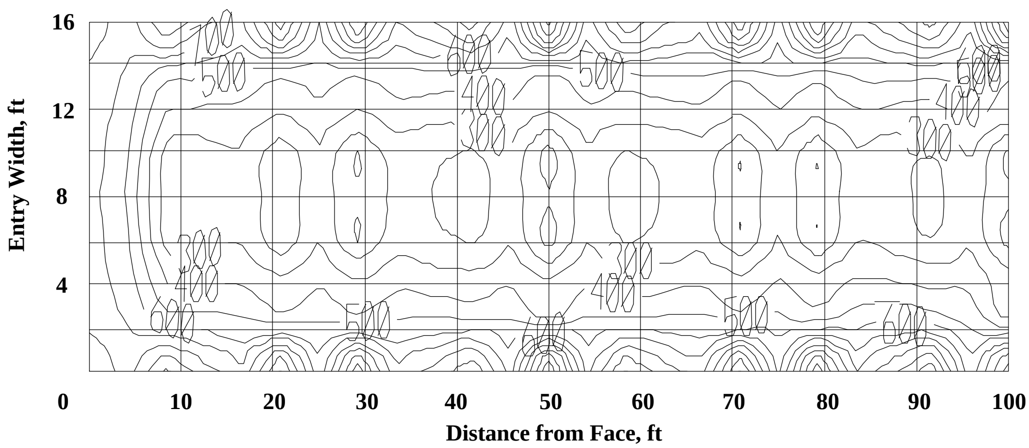
Fig. 4-2 Von Mises Stress in Entry Roof without Horizontal Stress



Entry 1

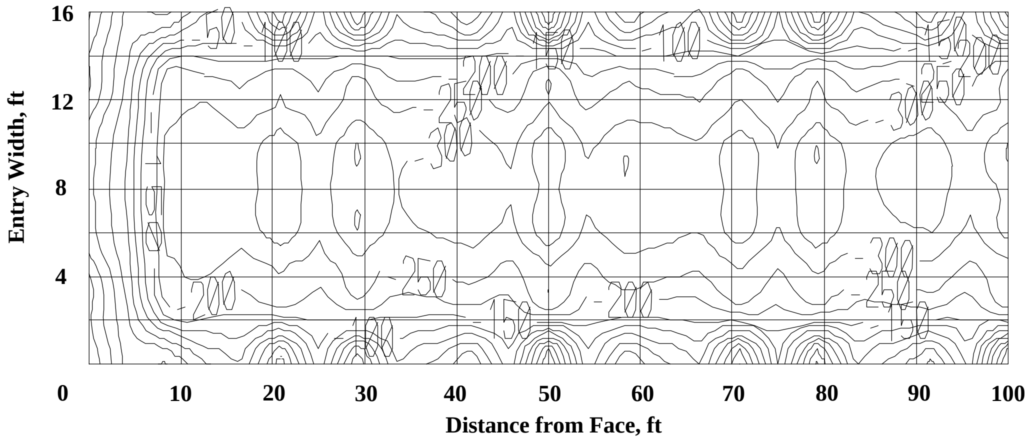


Entry 2

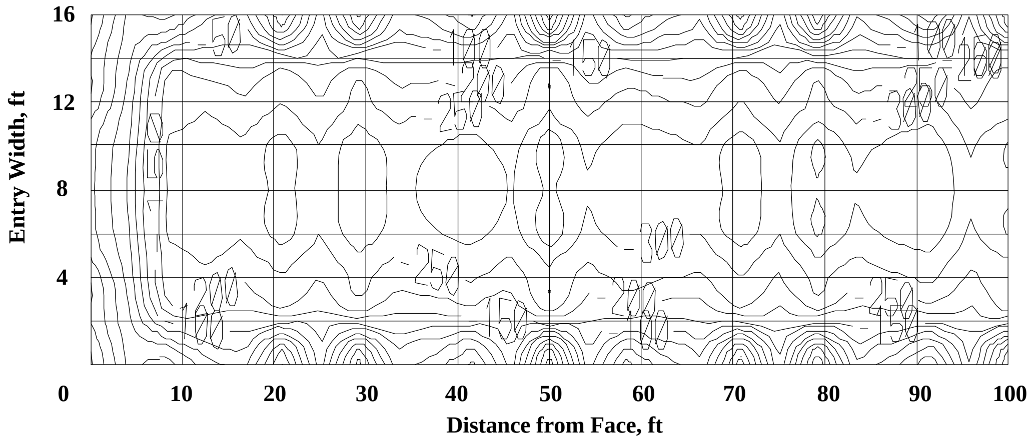


Entry 3

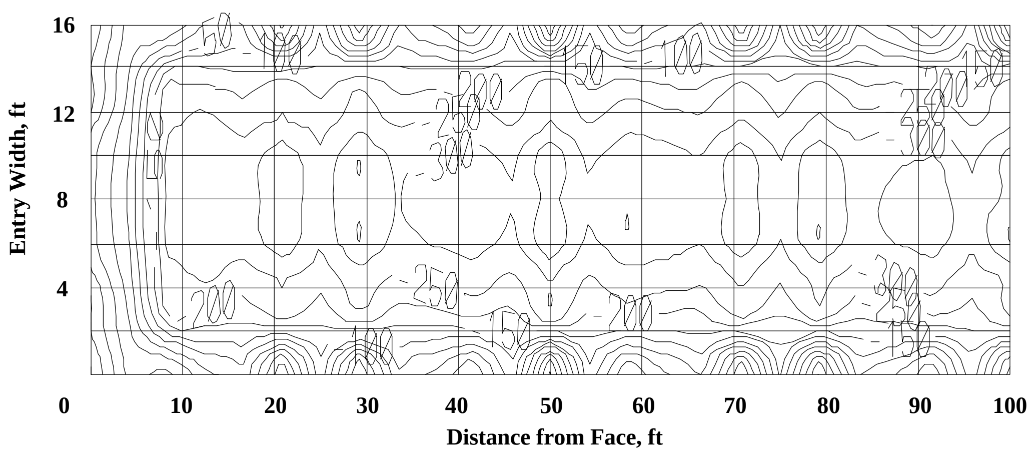
Fig. 4-3 Max. Principal Stress in Entry Roof without Horizontal Stress



Entry 1



Entry 2



Entry 3

Fig. 4-4 Min. Principal Stress in Entry Roof without Horizontal Stress

4.3 Influence of Stress Angle on Roof Stress

The initial study confirms that the horizontal stress has a significant influence on the entry roof. In a high horizontal stress field, the pattern of stress in the immediate roof is different from that without horizontal stress. In the following sections, the effects of different factors, such as the stress angle and the stress ratio, on the stresses at the roof line level will be analyzed. In this section, the influence of the stress angle is studied.

4.3.1 Influence of Stress Angle on the Roof Stress in Entries

The stress angle between the maximum horizontal stress and the direction of entry development has a very significant effect on the roof stability. In this study, the simulated angles are 0^0, 15^0, 30^0, 45^0, 60^0, 75^0, and 90^0, respectively (see Fig. 4-1). In the model the horizontal stresses are 3,000 and 1,500 psi, respectively, and the simulated overburden depth is 800 ft. The maximum horizontal stress comes from the solid side of entry 1.

Fig. 4-5 shows the Von-Mises Stress in the immediate roof when the angle is 30^0. This figure indicates that the stresses in the immediate roof can be fully understood by means of analyzing the stress changes along lines L1~L5 in each entry. The lines L1~L5 are at the roof line level. Lines L1 and L5 are respectively located at the upper corners of each entry. Line L3 is in the center of the entry roof. Lines L2 and L4 are near line L1 and line L5, respectively. The distance from L2 to L1 (also from L4 to L5) is 1.5 ft. In addition, the stresses at the points, numbered P1~P15 as shown in Fig. 4-5, can also indicate the stress changes in the immediate roof of each entry. Points P1~P5 are in the cross section A-A, points P6~P10 are in the cross section B-B, and points P11~P15 are in the cross section C-C. The all points are on lines L1~L5, respectively. The cross section A-A is located at the entry face. The distance between the cross section B-B and the cross section A-A is 3.0 ft, and it is 50 ft from the cross section C-C to the cross section A-A.

In the following sections, the stresses in each entry are analyzed.

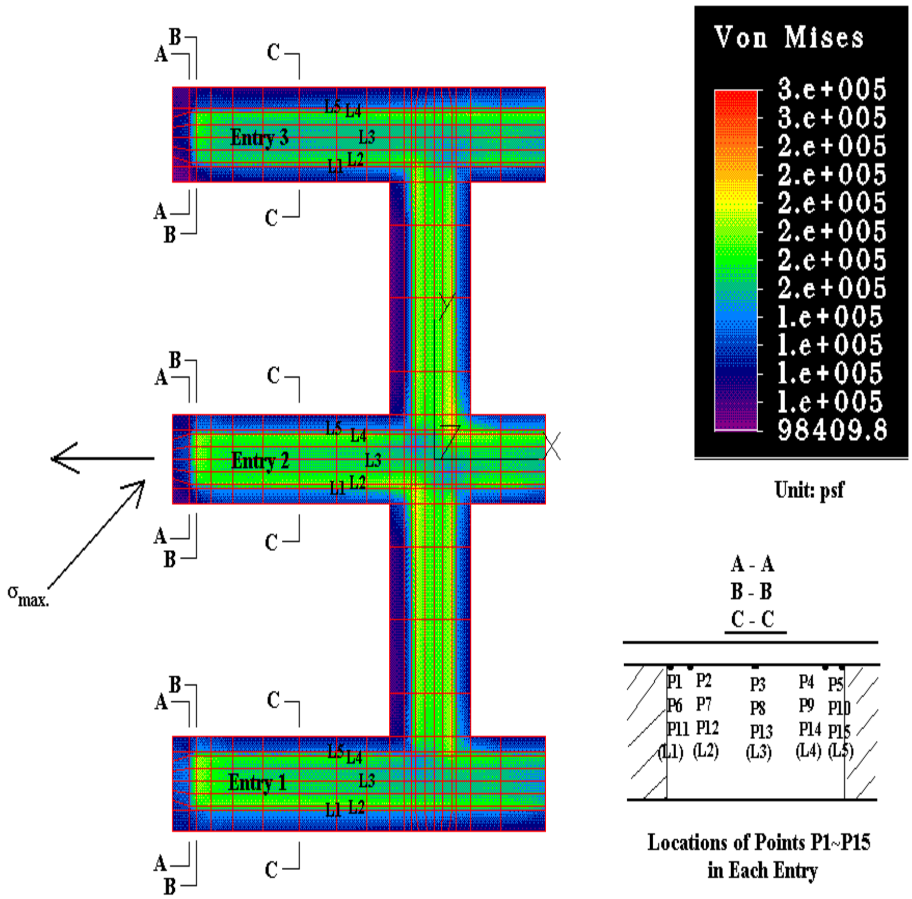


Fig. 4-5 Locations of Measurement Lines and Points

Stress Distributions in Entry 1

a. Von-Mises Stress

The Von-Mises stress distributions in the immediate roof are shown in Fig. 4-6. It indicates that the Von-Mises stress with horizontal stress is much larger than that without horizontal stress. In addition, the stress distributions are not symmetrical. For example, the stress in one side of roof (along L1 and L2) is larger than that in the other side (along L4 and L5). In addition, the stress changes significantly in a range of about 20 ft from the entry face. Beyond that range, the stress keeps constant except near the intersection between the entry and the crosscut. Therefore, the typical stress distributions can be studied by means of analyzing the stresses in the three cross sections A-A, B-B, and C-C.

In the cross section A-A, the Von-Mises stress change with the angle is shown in Fig. 4-7(a). At point P1 (at one corner), the stress increases with the angle slightly. It reaches the maximum when the angle is about 75^0, then reduces. At point P5 (at the other corner), the Von-Mises stress increase with the angle from 0^0 to 45^0, then reduces from 45^0 to 90^0. The stress at point P5 is always larger than that at point P1, which indicates that the stress concentration occurs at point P5 (one corner). However, the larger stress in this cross section does not occur at the corners, it appears in the middle point P3, when the angle is from 0^0 to 45^0. When the angle is larger than 45^0, the stress difference between these points is small. Generally speaking, the stress in the cross section A-A increases with the angle from 0^0 to 45^0, then decreases from 45^0 to 90^0, and reaches the minimum when the angle is 90^0.

In the cross section B-B, the Von-Mises stress is larger than that in the cross section A-A. The Von-Mises stress at the roof line level is always concentrated at the rib sides of entry 1, as shown in Fig. 4-7(b). In the two rib sides, the stress increases with the angle from 0^0 to 60^0, then decreases from 60^0 to 90^0. However, the stresses at the two rib sides are different. At the solid side (along line L1), the stress is larger than that at the other side (along line L5), namely, the stresses at points P6 and P7 are larger than those at points P9 and P10. At the center (P8), the stress increases with the angle from 0^0 to 30^0, then decreases from 30^0 to 90^0. In this cross section, the roof is in a worse condition, when the angle is about 60^0.

As shown in Fig. 4-6, the pattern of stress distribution depends on the angle. When the angle is equal to or less than 45^0, the stress distributes with the following trend: it increases quickly from the cross section A-A to the cross section B-B where it reaches the maximum. It then decreases and remains unchanged in the other sections. There is a peak in the stress distribution along each line. This peak appears in the cross section B-B. When the angle is larger than 45^0, the stress increases quickly from the cross section A-A to the cross section B-B, then increases very slightly. Fig. 4-7(c) shows the stress change with the angle in the cross section C-C, which indicates the stress situation in the normal entry (without the influence of development). In this cross section, the stress in the rib sides is larger than that at the center of the roof. The stresses in the two rib sides increase with the angle from 0^0 to 60^0, then decrease slightly from 60^0 to 90^0. At the center of the roof, the stress change with the angle is not large. In this cross section, the stress in the solid rib side is larger than that in the other side.

In entry 1, the Von-Mises stress is concentrated at the two rib sides. The stress in the solid rib side is larger than that in the other side. In addition, when the angle is larger than 30^0, the Von-Mises stress increase significantly with the angle. It reaches the maximum when the angle is about 60^0. The stress in the cross section A-A is smaller than those in the cross sections B-B and C-C. When the angle is equal to or less than 45^0, the maximum stress occurs in the cross section B-B. When the angle is larger than 45^0, the maximum stress occurs in the cross section B-B or cross section C-C or both.

b. Minimum Principal Stress

The purpose to determine the minimum principal stress is to check if tensile stress occurs in the roof line level. If tensile stress occurs in the immediate roof, a tensile failure may occur because rock material has very low tensile strength.

The minimum principal stresses in the three cross sections A-A, B-B, and C-C are shown in Fig. 4-8. In the cross section A-A, there is no tensile stress, as shown in Fig. 4-7(a). In the two rib sides (at two corners), the stresses are larger. They increase and decrease with the angle. There are two peaks in the stress distributions when the angle is 15^0 and 75^0, respectively. At the other points, the stress increases with the angle from 0^0 to 30^0, and then decrease from 30^0 to 90^0. It reaches the minimum when the angle is 90^0.

In the cross section B-B, the minimum principal stress at the rib sides slightly increases with the angle, as shown in Fig. 4-8(b). At the other points, the stress is smaller. At the center of the roof, tensile stress occurs although it is small. At points P7 and P9, the stresses are slightly larger than that at point P8. The angle influence on the stresses at points P7~P9 can be ignored.

The minimum principal stress distribution in the cross section C-C is similar to that in the cross section B-B, as shown Fig. 4-8(c). The stress at the rib sides increases slightly with the angle. The angle influence on the stresses at the other points is very small.

The minimum principal stress at the roof line level in entry 1 increases slightly with the angle at the two rib sides. At the solid rib side, it reaches the maximum when the angle is about 75^0. At the other side, it reaches the maximum when the angle is about 90^0. However, the angle influence on the stress in the other part of the roof can be ignored. In addition, tensile stress may occur in the center of the roof.

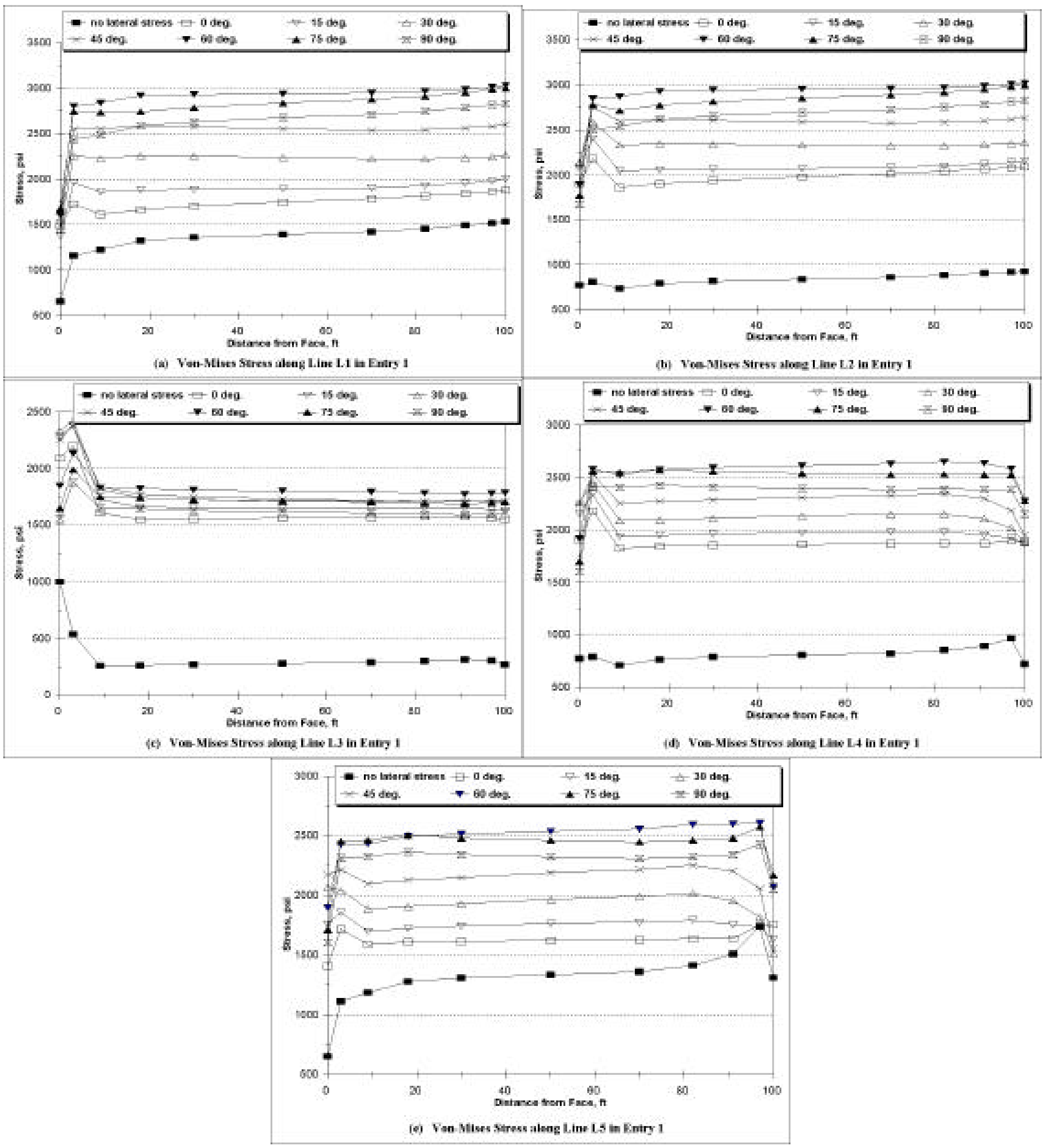
c. Maximum Principal Stress

The maximum principal stresses at the roof line level in the three cross sections are shown in Fig. 4-9. In the cross section A-A, the stresses at points P2 and P3 increase with the angle from 0^0 to 15^0, and then decrease, as shown in Fig. 4-9(a). At point P4, the stress increases with the angle from 0^0 to 30^0, and then decreases. At the corner (P5), the stress increase with the angle from 0^0 to 60^0, and then decrease. At the other corner (P1), the stress is smaller. The angle influence on it is very small.

In the cross section B-B, the maximum principal stress at the solid rib side (P6) increases with the angle from 0^0 to 75^0, then decrease slightly, as shown in Fig. 4-9(b). It reaches the maximum when the angle is about 60^0~75^0. At the other rib side (P10), the stress increases with the angle. It reaches the maximum when the angle is about 90^0. However, the stress at this rib side is smaller than that in the solid rib side. The stresses at points P7 and P9 change with the angle. They both reach the maximum when the angle is about 60^0. At the center of the roof (P8), the stress decreases with the angle.

In the cross section C-C, the maximum principal stresses at the two rib sides (P11 and P15) increases with the angle from 0^0 to 60^0, and then increases very slightly, as shown in Fig. 4-9(c). The stresses at points P12 and P14 also increase with the angle in the same way. However, at the center of the roof (P13) the stress does not change with the angle.

In entry 1, the maximum principal stress increases with the angle. When the angle ranges from 60^0 to 90^0, the stress reaches the maximum. In addition, the stress is also concentrated at the two rib sides. The stress in the roof line level is larger at the solid rib side than that at the other rib side.



(a) Von-Mises Stress along Line L1 in Entry 1

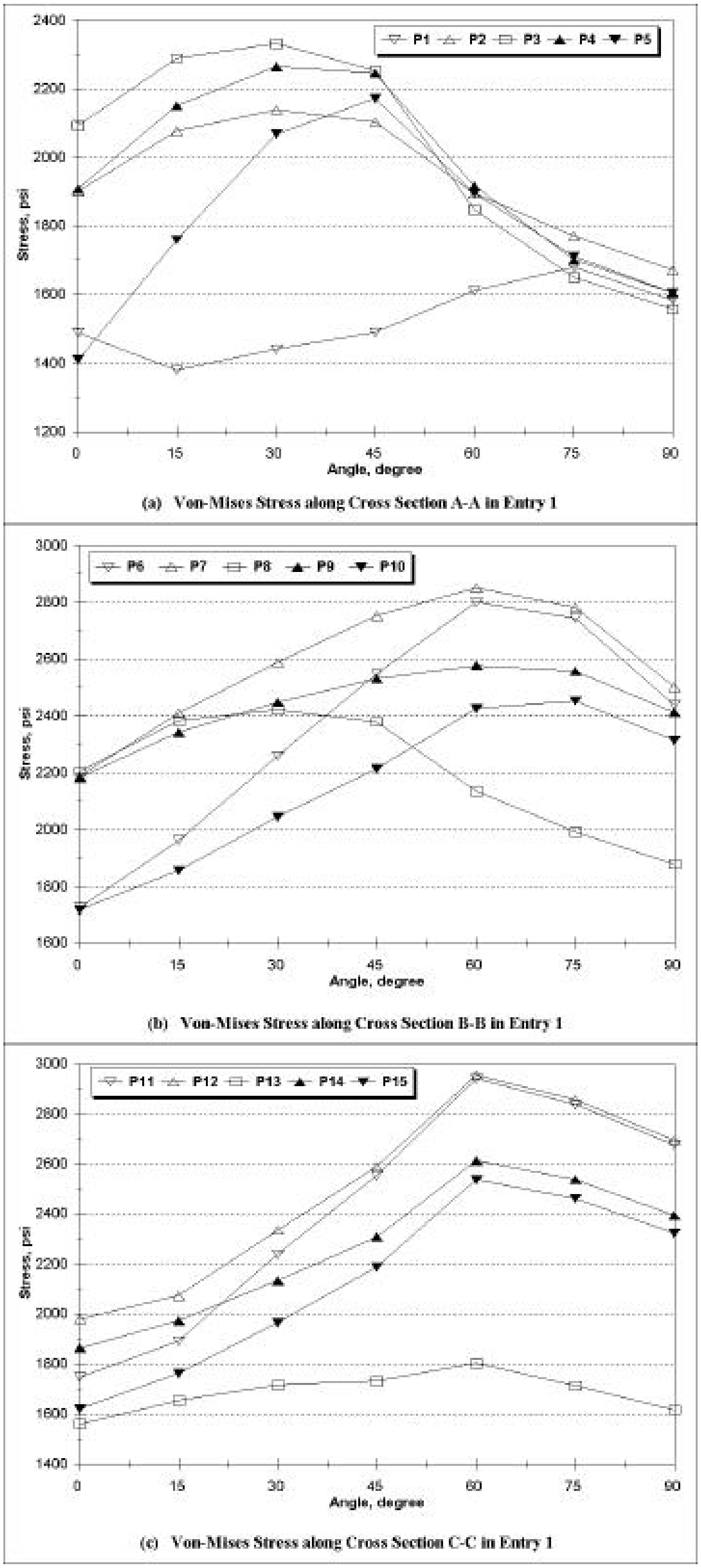
(b) Von-Mises Stress along Line L2 in Entry 1

(c) Von-Mises Stress along Line L3 in Entry 1

(d) Von-Mises Stress along Line L4 in Entry 1

(e) Von-Mises Stress along Line L5 in Entry 1

Fig. 4-6 Von-Mises Stress Change with the Angle in Entry 1



(a) Von-Mises Stress along Cross Section A-A in Entry 1

(b) Von-Mises Stress along Cross Section B-B in Entry 1

(c) Von-Mises Stress along Cross Section C-C in Entry 1

Fig. 4-7 Von-Mises Stress Change with the Angle in Different Cross Sections of Entry 1

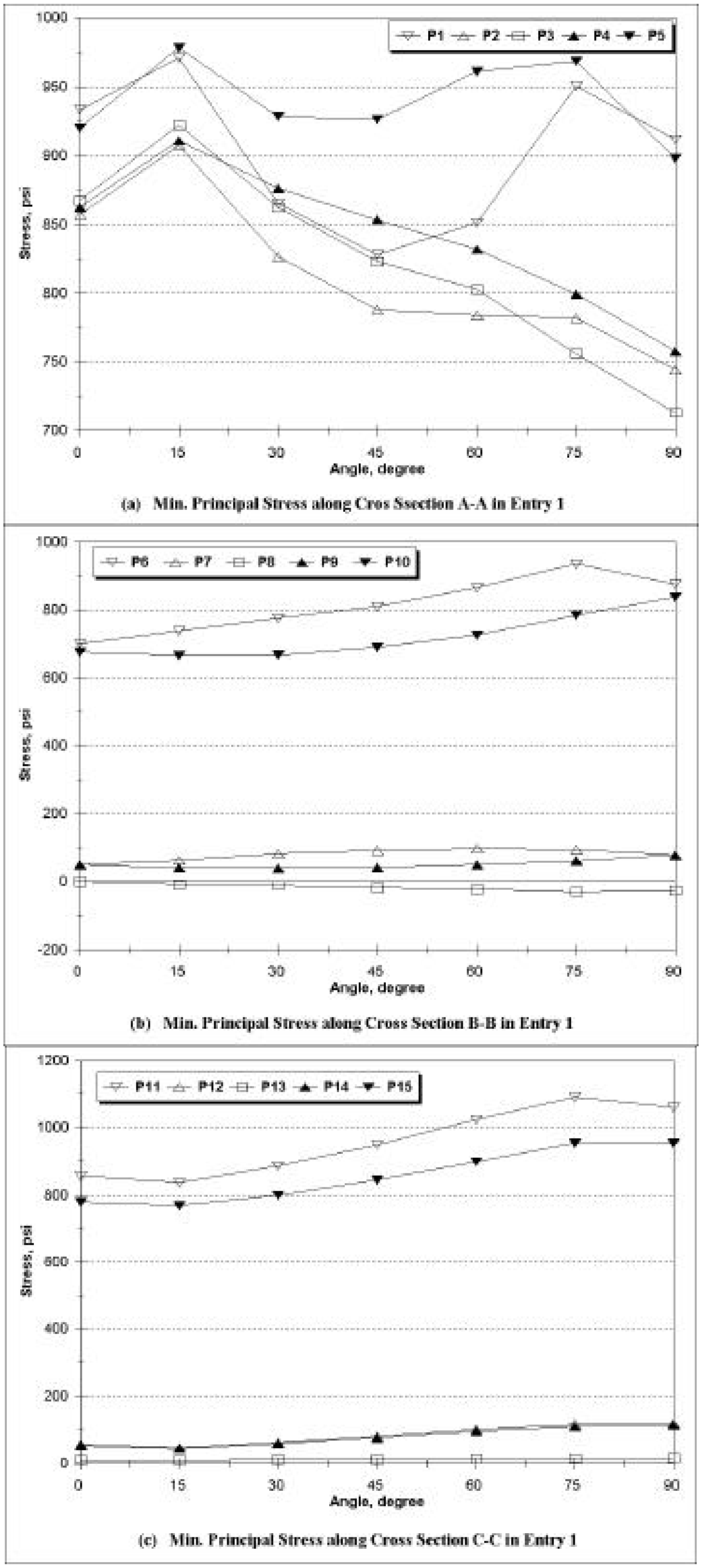


Fig. 4-8 Min. Principal Stress Change with the Angle in Different Cross Sections of Entry 1

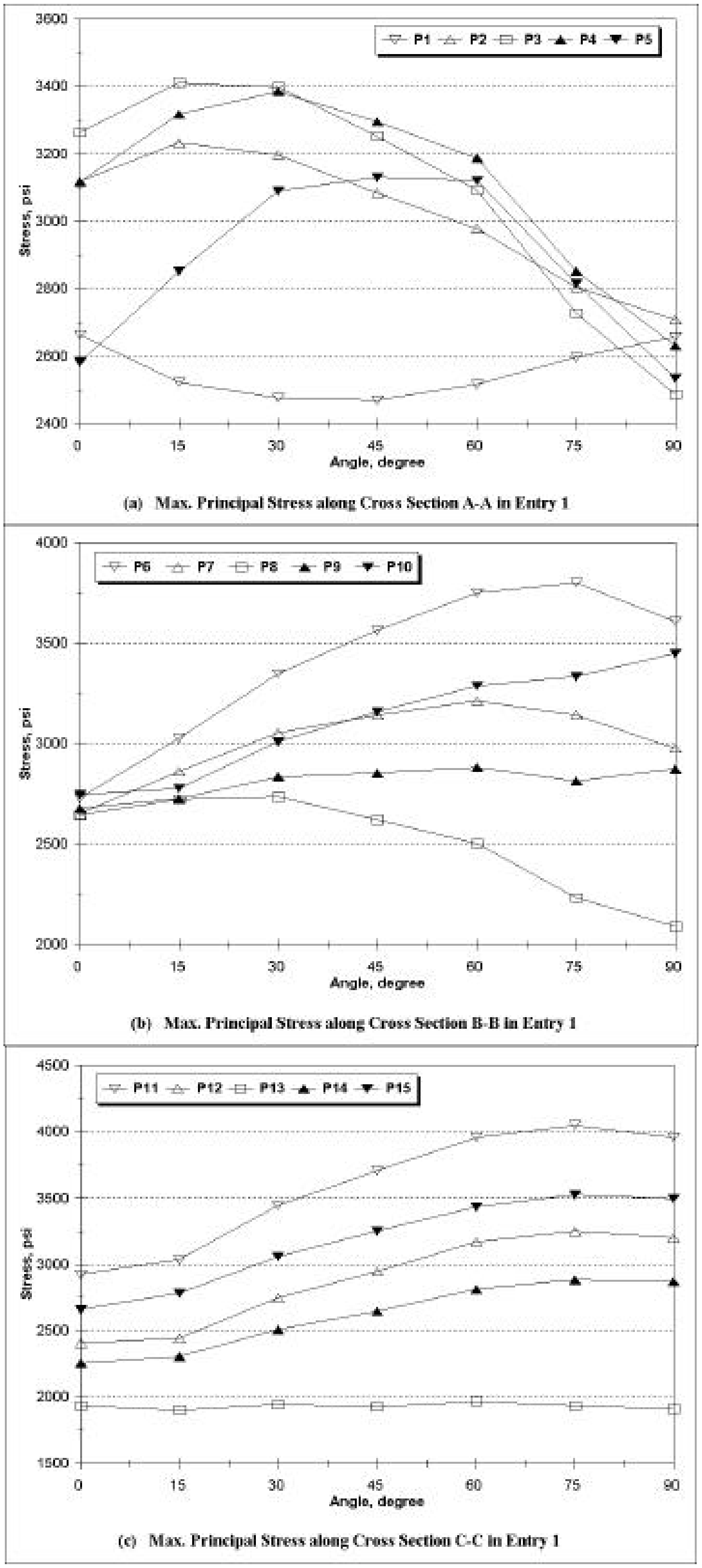


Fig. 4-9 Max. Principal Stress Change with the Angle in Different Cross Sections of Entry 1

Stress Distributions in Entry 2

a. Von-Mises Stress

In entry 2, the Von-Mises stress in the roof line level is shown in Fig. 4-10 for different stress angles. It is similar to that in entry 1, except at the intersection between entry 2 and the crosscuts. Under the high horizontal stress, the stress is much larger than that without the horizontal stress. In addition, the influence of the stress angle on the roof stress is very significant, especially at the two rib sides. The stress angle causes changes not only in the stress magnitude but also in its distribution pattern. When the stress angle changes from 0^0 to 45^0, the Von-Mises stresses at the two rib sides (along lines L1, L2, L4, and L5) increase quickly from the cross section A-A to the cross section B-B, and then decrease rapidly. There is a peak in the stress distribution along each line. When the stress angle is larger than 45^0, the stresses increase quickly from the cross section A-A to the cross section B-B, and then increase very slightly or keep unchanged. However, in the center of the roof (along line L3), the Von-Mises stress is distributed with the following trend: it increases quickly from the cross section A-A to the cross section B-B when the angle ranges from 0^0 to 90^0, then decreases rapidly and finally keep unchanged. It is found from Fig. 4-10 that the stress distributions in the three cross sections A-A, B-B, and C-C can represent the stress situation in entry 2. Therefore, the stresses in these cross sections are analyzed in the following.

In the cross section A-A, the Von-Mises stress changes with the angle, as shown in Fig. 4-11(a). At point P5 (at one corner), the stress increases with the angle from 0^0 to 45^0, and then decreases from 45^0 to 90^0. It reaches the maximum when the angle is 45^0. At point P1 (the other corner), the stress also changes with the angle. But, compared with the stress at point P5, the stress at point P1 is smaller when the angle ranges from 0^0 to 75^0. This indicates that the stress is concentrated at one corner (P5). When the angle is from 75^0 to 90^0, the stresses at the two corners reach the same. The stresses at points P2 and P3 change in the same way. The stresses increase slightly with the angle from 0^0 to 15^0, and then decrease gradually from 15^0 to 90^0. At point P4, the stress increases slightly with the angle from 0^0 to 45^0, then decreases from 45^0 to 90^0. Generally speaking, the stresses at the cross section A-A are becoming the same when the angle is larger than 45^0.

In the cross section B-B, the influence of the stress angle on the Von-Mises stress is significant, as shown in Fig. 4-11(b). In this cross section, the stress is larger than that in the cross section A-A. In addition, the stresses are concentrated at the two rib sides. There the stresses increase with the angle from 0^0 to 60^0, and then decrease slightly from 60^0 to 90^0. When the angle is about 60^0~75^0, the Von-Mises stresses at the two rib sides reach the maximum. Moreover, the stresses at the two rib sides are not same. At the side near entry 3 (P9 and P10), the stress is larger than that at the other side (P6 and P7). But the difference between them is not large, less than 100 psi. At the center of the roof, the Von-Mises stress decreases with the angle. When the angle is 90^0, it reaches the minimum.

The Von-Mises stress change with the stress angle in the cross section C-C is shown in Fig. 4-11(c). It indicates that the Von-Mises stress is concentrated at the two rib sides and that the angle has a significant influence on the stress at these sides where the stresses increase with the angle from 0^0 to 60^0, and then decrease slightly from 60^0 to 90^0. When the angle is about 60^0, the stresses reach the maximum. In this cross section, the stress at the side near entry 3 (P14 and P15) is larger than that at the other side (P11 and P12). At the center of the roof (P13), the angle influence on the stress is small.

In entry 2, the stress angle has a significant influence on the Von-Mises stress at the roof line level, especially at the rib sides. The stress at the two rib sides increases rapidly with the angle from 0^0 to 60^0, and then decreases slightly from 60^0 to 90^0. When the angle is from 60^0 to 75^0, the stress reaches the maximum. In addition, the stress at the side near entry 3 is larger than that at the other side. At the center of roof, the angle influence on the Von-Mises stress in the roof line level is not significant.

b. Minimum Principal Stress

The minimum principal stresses in the three cross sections A-A, B-B, and C-C are shown in Fig. 4-12. In the cross section A-A, no tensile stress occurs, as shown in Fig. 4-12(a). At the corners (points P1 and P5), the minimum principal stresses are larger than those at the other points. The stress angle has some influence on the minimum principal stresses at the two corners. At point P5, the stress is larger than that at point P1, and it changes with the angle from 0^0 to 90^0. The change is about 50 psi. At the other points, the stresses increase with the angle from 0^0 to 15^0, and then decreases from 15^0 to 90^0. When the angle is 90^0, the stresses at these points reach the minimum.

In the cross section B-B, the minimum principal stresses at the rib sides (points P6 and P10) increase gradually with the angle from 0^0 to 90^0, as shown in Fig. 4-12(b). When the angle is larger than 60^0, the stress nearly keeps unchanged. In addition, the stress at the side near entry 3 (P10) is a little larger than that at the other side (P6). At points P7 and P9, the stress is very small, under 100 psi. At the center of the roof (P8), tensile stress occurs. It increases very slightly with the angle.

The minimum principal stress in the cross section C-C is shown in Fig. 4-12(c). It is similar to that in the cross section B-B. At the rib sides (points P11 and P15), the stresses are near the same and larger than those in the other points. The stresses increase with the angle from 0^0 to 90^0. At points P12 and P14, the stresses increase slightly with the angle from 0^0 to 90^0. But the stress values are less than 100 psi. At the center of roof, the stress does not change with the angle. It is near 0 psi.

The minimum principal stress at the roof line level in entry 2 increases slightly with the angle from 0^0 to 90^0 at the rib sides. When the angle is 60^0 ~ 90^0, the stress reaches the maximum. Although the stress at the side near entry 3 is larger than that at the other side, the difference between them is very small and can be ignored. At the other points, the angle influence on the minimum principal stress is very small. At the center of the roof, tensile stress may occur.

c. Maximum Principal Stress

The maximum principal stresses at the roof line level in the three cross sections are shown in Fig. 4-13. In the cross section A-A, the stress distributions are similar to those of the Von-Mises stress (comparing Fig. 4-13(a) with Fig. 4-11(a)). At the corner (point P5), the maximum principal stress increases with the angle from 0^0 to 45^0, and then decreases from 45^0 to 90^0. At the other corner (point P1), the stress decreases with the angle from 0^0 to 30^0, reduces very slightly from 30^0 to 60^0, and then increases from 60^0 to 90^0. The stress at point P5 is larger than that at point P1, which indicates that the stress is concentrated at one corner (P5). At other points, the stresses decrease with the angle from 0^0 to 90^0. When the angle is from 0^0 to 15^0, the maximum principal stress at the center point (P3) in the cross section A-A is the maximum.

In the cross section B-B, the stresses at the two rib sides (P6 and P10) increase with the angle from 0^0 to 90^0, as shown in Fig. 4-13(b). When the angle is more than 60^0, the stresses increase slightly. The stresses reach the maximum when the angle is 90^0. The stress at the rib side near entry 3 is larger than that at the other side. But the difference between them decreases with increase in the angle. At the center (P8) of the roof, the stress decreases with the angle from 0^0 to 90^0, and reaches the minimum when the angle is 90^0.

The maximum principal stress change with the angle in the cross section C-C is similar to that in the cross section B-B, as shown in Fig. 4-13(c). At the two rib sides (P11 and P15), the stresses increase with the angle from 0^0 to 90^0. When the angle is more than 60^0, the stresses increase slightly. Although the stress at the side near entry 3 is larger than that at the other side, the difference between them is small and decrease with the angle. At the center (P13), the stress does not change with the angle.

In entry 2, the maximum principal stresses are concentrated at the two rib sides. They increase with the stress angle from 0^0 to 90^0. When the angle is more than 60^0, the stresses increase slightly. When the angle is from 60^0 to 90^0, the stress reaches the maximum. In addition, the stress at the rib side near entry 3 is larger than that at the other side. But the difference between them is small and decreases with the angle.

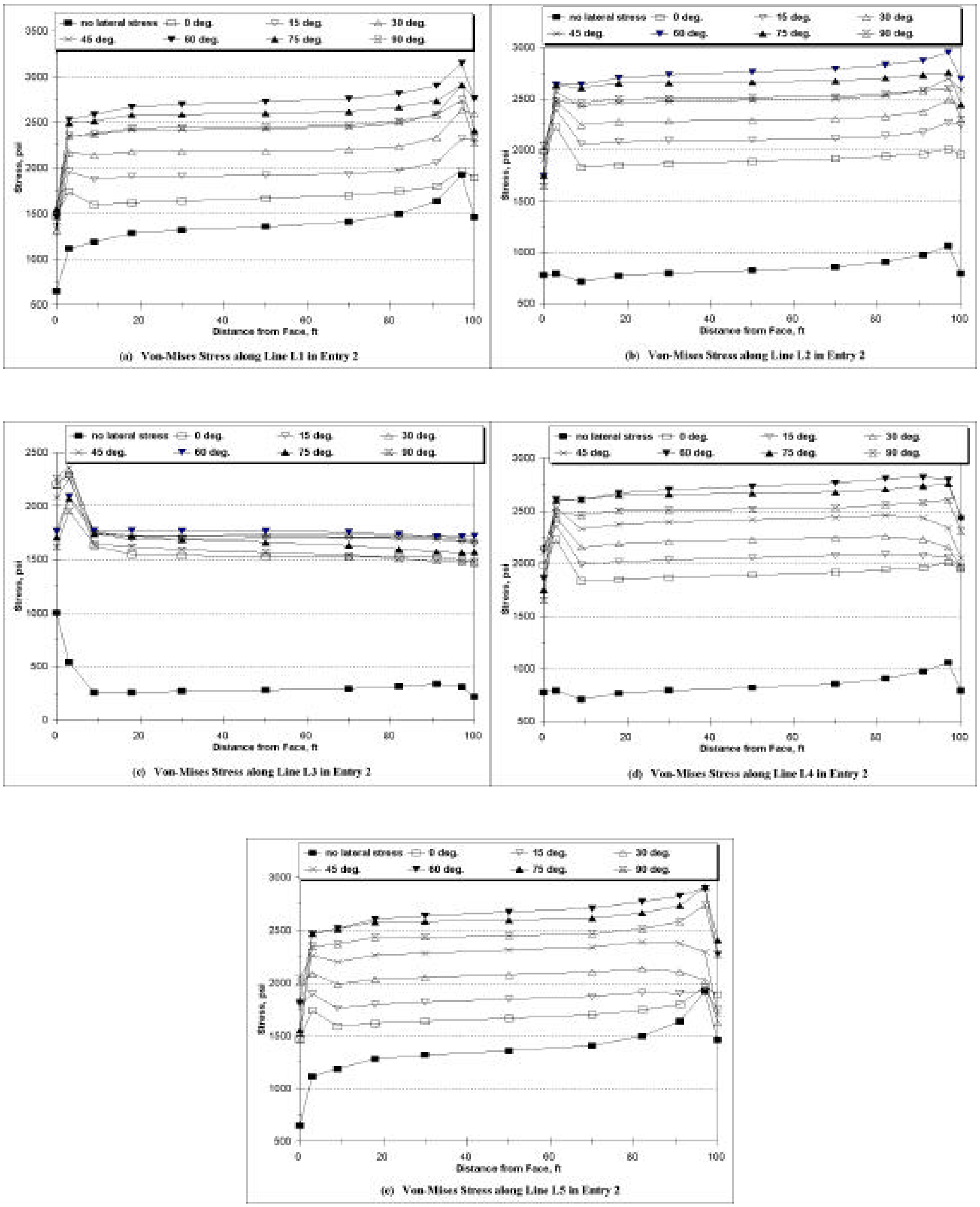


Fig. 4-10 Von-Mises Stress Change with the Stress Angle in Entry 2

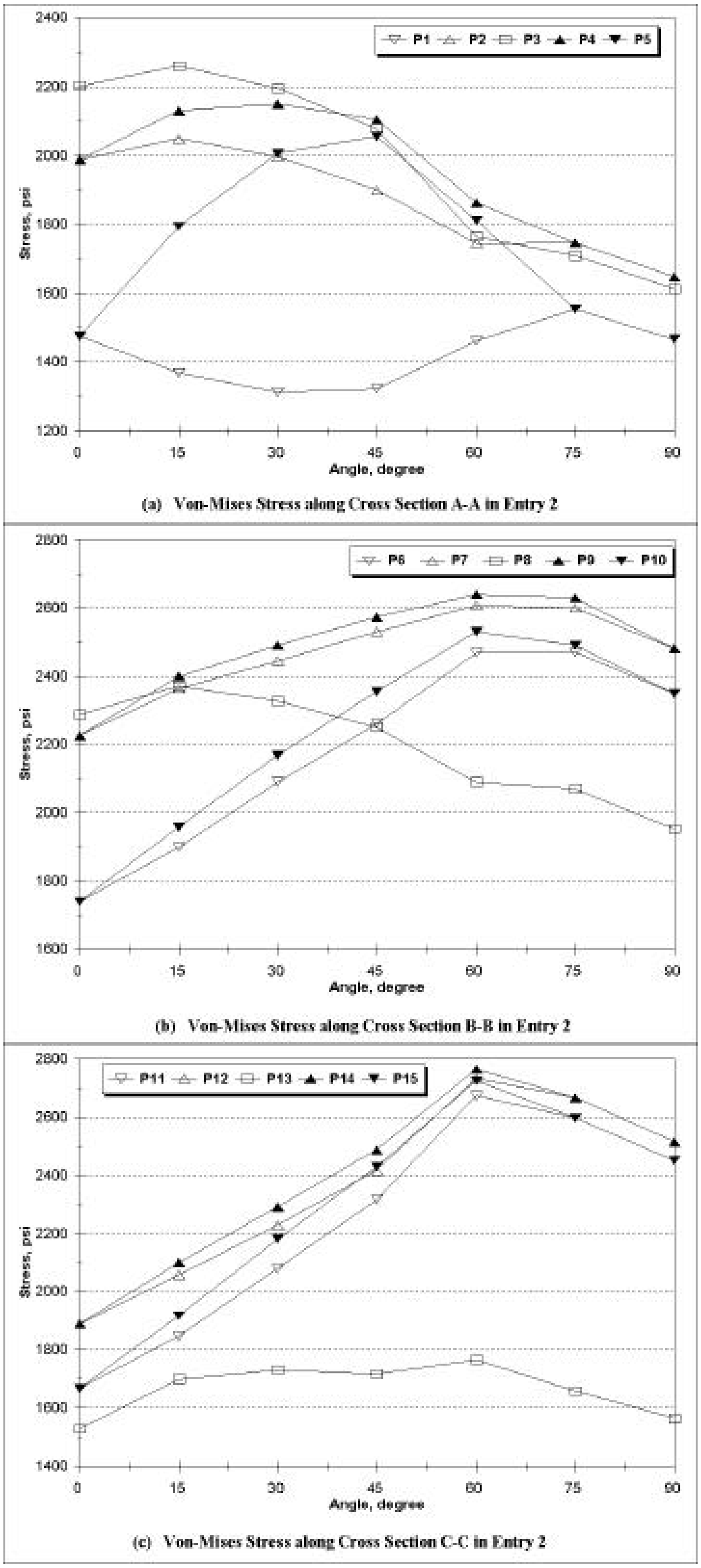


Fig. 4-11 Von-Mises Stress Change with the Angle in Different Cross Sections of Entry 2

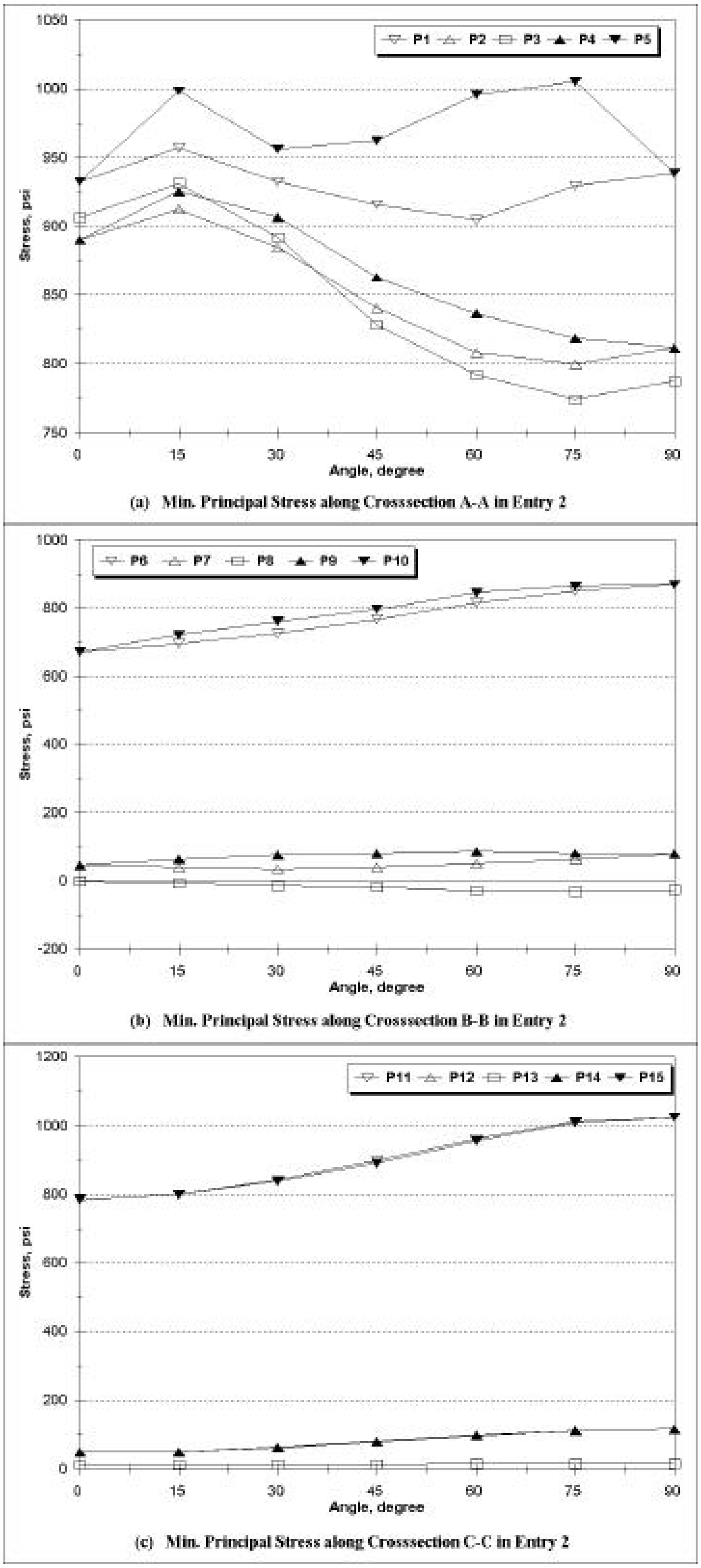


Fig. 4-12 Min. Principal Stress Change with the Angle in Different Cross Sections of Entry 2

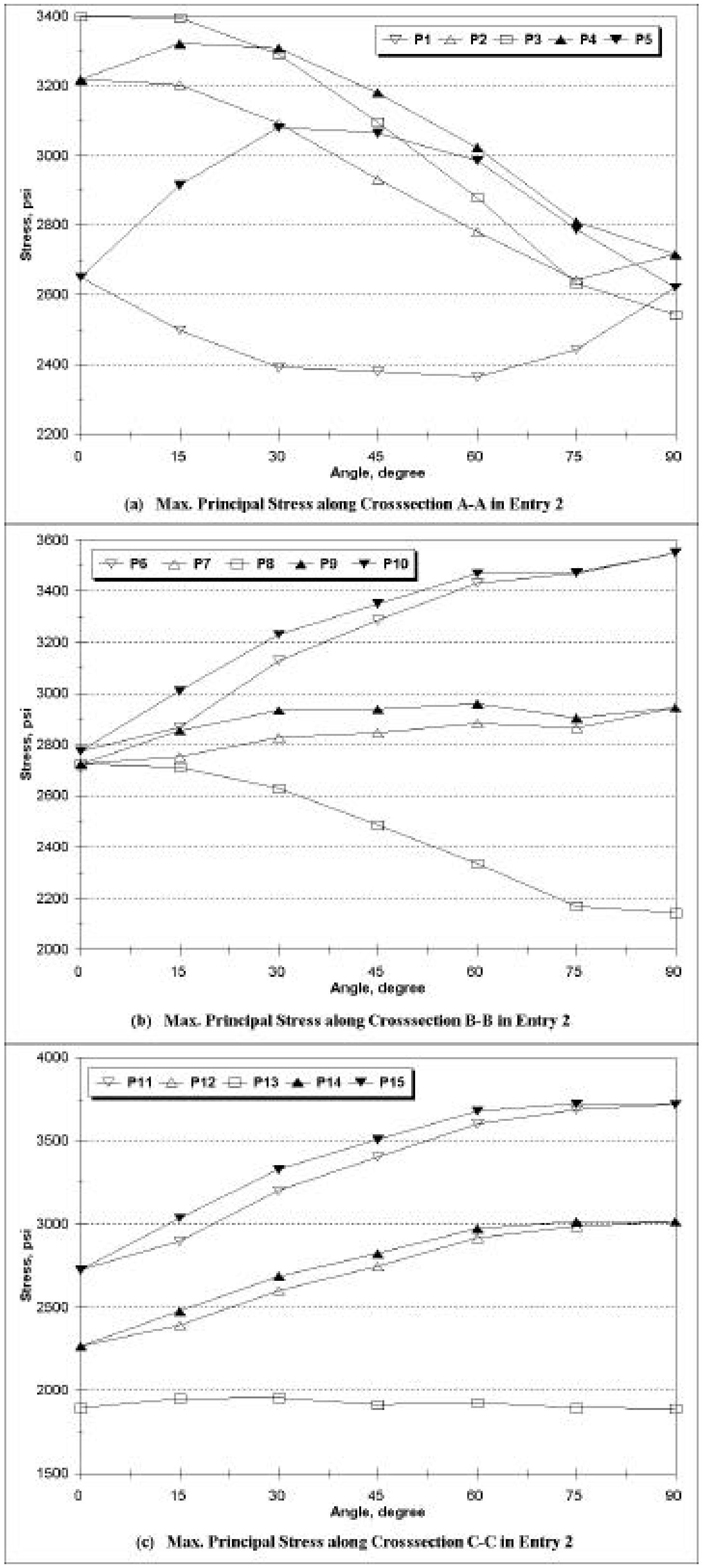


Fig. 4-13 Max. Principal Stress Change with the Angle in Different Cross Sections of Entry 2

Stress Distributions in Entry 3

a. Von-Mises Stress

The Von-Mises stress in the roof line level of entry 3 is shown in Fig. 4-14 for different stress angles. It is similar to that in entry 1. Under the high horizontal stress, the stress is much larger than that without the horizontal stress. In addition, the influence of the stress angle on the stress distribution is very significant, especially at the two rib sides. The stress angle causes changes not only in the stress magnitude but also in its distribution pattern. When the angle changes from 0^0 to 45^0, the Von-Mises stresses at the two rib sides (along lines L1, L2, L4, and L5) increase quickly from the cross section A-A to the cross section B-B, and then decrease rapidly. There is a peak in the stress distribution along each line. When the angle is larger than 45^0, the stresses increase quickly from the cross section 1 to the cross section 2, then increase very slightly or keep unchanged. However, at the center of the roof (along line L3), the Von-Mises stress is distributed with the following trend: it increases quickly from the cross section A-A to the cross section B-B when the angle ranges from 0^0 to 90^0, then decreases rapidly and finally keep unchanged. It is also found from Fig. 4-10 that the stress distributions in the three cross sections A-A, B-B, and C-C can represent the stress situation in entry 2. Therefore, the stresses in these cross sections are analyzed in the following.

In the cross section A-A, the Von-Mises stress changes with the stress angle, as shown in Fig. 4-15(a). At point P5 (at one corner), the stress increases with the angle from 0^0 to 30^0, then increases very slightly from 30^0 to 60^0, and finally decreases from 60^0 to 90^0. It reaches the maximum when the angle is 30^0 to 60^0. At point P1 (the other corner), the stress decreases with the angle from 0^0 to 45^0, and then increases from 45^0 to 75^0. When the angle is 75^0 to 90^0, the stress at point P1 decreases slightly. The stress at point P1 is less than that at point P5. This indicates that the stress is concentrated at point P5 (a corner). At points P2 and P3, the stresses decrease with the angle from 0^0 to 90^0. At point P4, the stress increases with the angle from 0^0 to 30^0, and then gradually decreases from 30^0 to 90^0. Generally speaking, the Von-Mises stress in the cross section A-A decreases with the angle from 30^0 to 90^0.

In the cross section B-B, the influence of the stress angle on the Von-Mises stress is significant, as shown in Fig. 4-15(b). In this cross section, the stress is larger than that in the cross section A-A. In addition, the stresses are concentrated at the two rib sides. At the rib side near entry 2 (point P6), the stresses increase with the angle from 0^0 to 60^0, and then decrease from 60^0 to 90^0. When the angle is about 60^0, the Von-Mises stress at this rib side reaches the maximum. At the other rib side (P10), the stress increases with the angle from 0^0 to 75^0, and then decreases from 75^0 to 90^0. The stress reaches the maximum when the angle is about 75^0. The stress at point P10 is larger than that at point P6. But the difference between them is not large. The maximum difference is about 100 psi. The stress at point P7 changes with the angle in the same way as at point P6. When the angle is about 60^0, the stress at point P7 reaches the maximum. But the stress at this point is larger than that at point P6. At point P9, the stress increases with the angle from 0^0 to 60^0, then nearly keeps unchanged from 60^0 to 75^0, but finally decreases from 75^0 to 90^0. The stress at point P9 is larger than those at the other points. At the center of the roof (point P8), the stress decreases with the angle. Generally, the stresses at the two rib sides are the maximum when the angle is from 60^0 to 75^0.

The Von-Mises stress change with the stress angle in the cross section C-C is shown in Fig. 4-15(c). It indicates that the stress is concentrated at the two rib sides and that the angle has a significant influence on the stress at these sides. At the rib side near entry 2 (P11), the stress increases with the angle from 0^0 to 60^0, then decreases from 60^0 to 90^0. When the angle is about 60^0, the stress reaches the maximum. At the other rib side (P15), the stress increases rapidly with the angle from 0^0 to 60^0, then slightly increases from 60^0 to 75^0, and finally decreases from 75^0 to 90^0. When the angle is about 75^0, the stress at this side is the maximum. In this cross section, the stress at the side near entry 2 (P11 and P12) is less than that at the other side (P14 and P15). At the center of the roof (P13), the angle influence on the stress is small.

In entry 3, the stress angle has a significant influence on the Von-Mises stress in the roof line level, especially at the rib sides. The stress at the rib side near entry 2 increases with the angle from 0^0 to 60^0, and then decreases slightly from 60^0 to 90^0. The stress at the other rib side increases rapidly with the angle from 0^0 to 60^0, then slightly increases from 60^0 to 75^0, and finally decreases from 75^0 to 90^0. The stress at this side is larger than that at the other side near entry 2. In the center of roof, the angle influence on the Von-Mises stress in the roof line level is not significant.

b. Minimum Principal Stress

The minimum principal stresses in the three cross sections A-A, B-B, and C-C are shown in Fig. 4-16. It is similar that in entry 2. In the cross section A-A, no tensile stress occurs, as shown in Fig. 4-16(a). At the corners (points P1 and P5), the minimum principal stresses are larger than those at the other points. The stress at point P5 is larger than that at point P1. The angle has some influence on the stresses at the two corners. At the other points, the stresses increase with the angle from 0^0 to 15^0, and then decreases from 15^0 to 90^0. When the stress angle is 90^0, the stresses at these points reach the minimum.

In the cross section B-B, the minimum principal stresses at the rib sides (points P6 and P10) increase slightly with the angle from 0^0 to 90^0, as shown in Fig. 4-16(b). When the angle is larger than 75^0, the stress nearly keeps unchanged. In addition, the stress at the side near entry 2 (P6) is a little less than that at the other side (P10). At points P7 and P9, the stress is very small, under 100 psi. At the center of the roof (P8), tensile stress occurs. It increases very slightly with the angle.

The minimum principal stress in the cross section C-C is shown in Fig. 4-16(c). It is similar to that in the cross section B-B. At the rib sides (points P11 and P15), the stresses increase with the angle from 0^0 to 75^0, and then nearly keep unchanged from 75^0 to 90^0. The stress at the rib side near entry 2 (P11) is less than that at the other side (P15). At points P12 and P14, the stresses increase slightly with the angle from 0^0 to 90^0. But the stress values are small. At the center of the roof, the stress does not change with the angle. It is near zero.

The minimum principal stress at the roof line level in entry 2 increases slightly with the angle from 0^0 to 90^0 at the rib sides. When the angle is 75^0 ~ 90^0, the stress reaches the maximum. The stress at the side near entry 2 is less than that at the other side. But the difference between them is less than 100 psi. At all other points, the angle influence on the minimum principal stress is very small. At the center of the roof, tensile stress may occur.

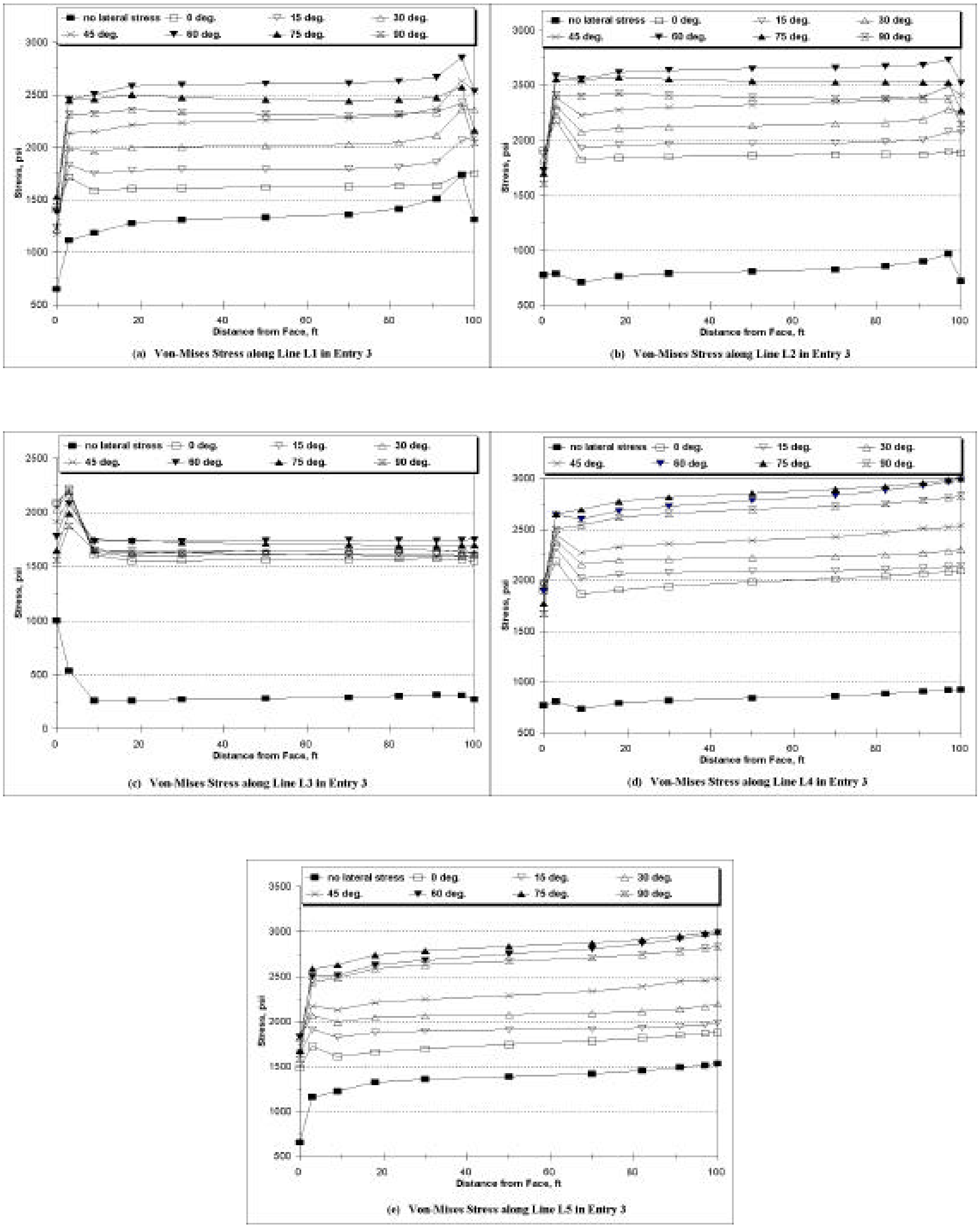
c. Maximum Principal Stress

The maximum principal stresses at the roof line level in the three cross sections are shown in Fig. 4-17. In the cross section A-A, the stress distributions are similar to those of the Von-Mises stress (comparing Fig. 4-17(a) with Fig. 4-15(a)). At the corner (point P5), the maximum principal stress increases with the angle from 0^0 to 30^0, stay more or less unchanged between 30^0 to 60^0, and then gradually decreases from 75^0 to 90^0. At the other corner (point P1), the stress decreases with the angle from 0^0 to 45^0, then increases from 45^0 to 90^0. The stress at point P5 is larger than that at point P1, which indicates that the stress is concentrated at point P5. At all other points, the stresses decrease with the angle from 0^0 to 90^0.

In the cross section B-B, the stress at the two rib sides (P6 and P10) increases with the angle from 0^0 to 90^0, as shown in Fig. 4-17(b). The stresses reach the maximum when the angle is 90^0. The stress at the rib side near entry 2 is less than that at the other side. At points P7 and P9, the stresses increase gradually with the angle from 0^0 to 90^0. At the center (P8) of the roof, the stress decreases with the angle from 0^0 to 90^0, and reaches the minimum when the angle is 90^0.

In the cross section C-C, the maximum principal stress change with the angle is shown in Fig. 4-17(c). At the side near entry 2 (P11 and P12), the stress increases rapidly with the angle from 0^0 to 60^0, then slightly increases from 60^0 to 75^0, and finally slightly decreases from 75^0 to 90^0. When the angle is about 75^0, the stress at point P11 reaches the maximum. At the other side, the stress increases quickly with the angle from 0^0 to 60^0, and then increases slightly from 60^0 to 90^0. The stress at the side near entry 2 is less than that at the other side. At the center (P13), the stress does not change with the angle.

In entry 3, the maximum principal stresses are concentrated at the two rib sides. The stress at the side near entry 2 increases with the angle from 0^0 to 75^0, and then slightly decreases from 75^0 to 90^0. The stress at the other side increases with the angle from 0^0 to 90^0. The stress at the side near entry 2 is less than that at the other side.



(a) Von-Mises Stress along Line L1 in Entry 3

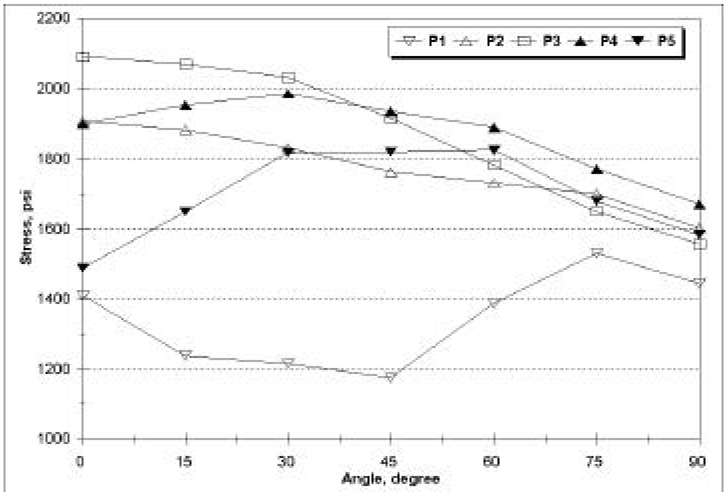
(b) Von-Mises Stress along Line L2 in Entry 3

(c) Von-Mises Stress along Line L3 in Entry 3

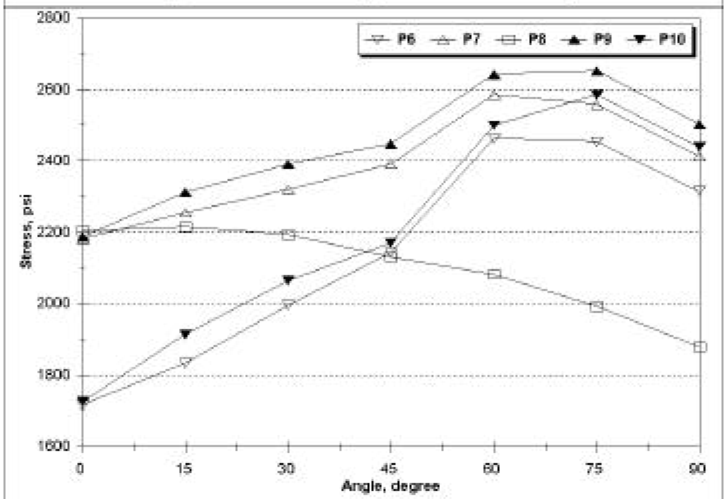
(d) Von-Mises Stress along Line L4 in Entry 3

(e) Von-Mises Stress along Line L5 in Entry 3

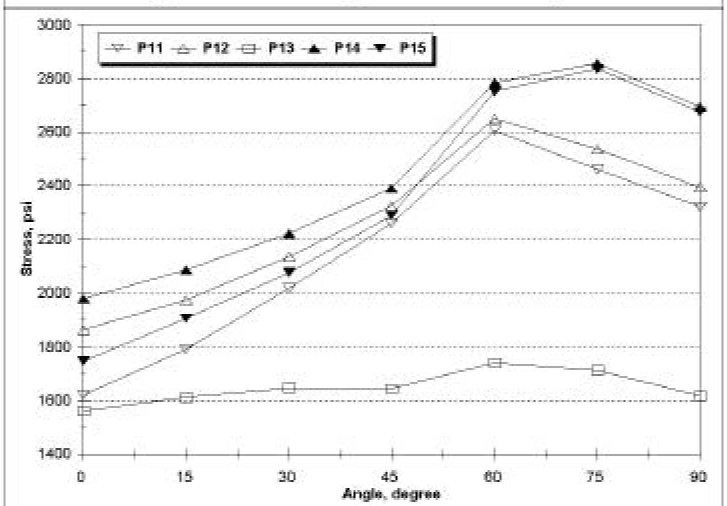
Fig. 4-14 Von-Mises Stress Change with the Angle in Entry 3



(a) Von-Mises Stress along Cross Section A-A in Entry 3



(b) Von-Mises Stress along Cross Section B-B in Entry 3



(c) Von-Mises Stress along Cross Section C-C in Entry 3

Fig. 4-15 Von-Mises Stress Change with the Angle in Different Cross Sections of Entry 3

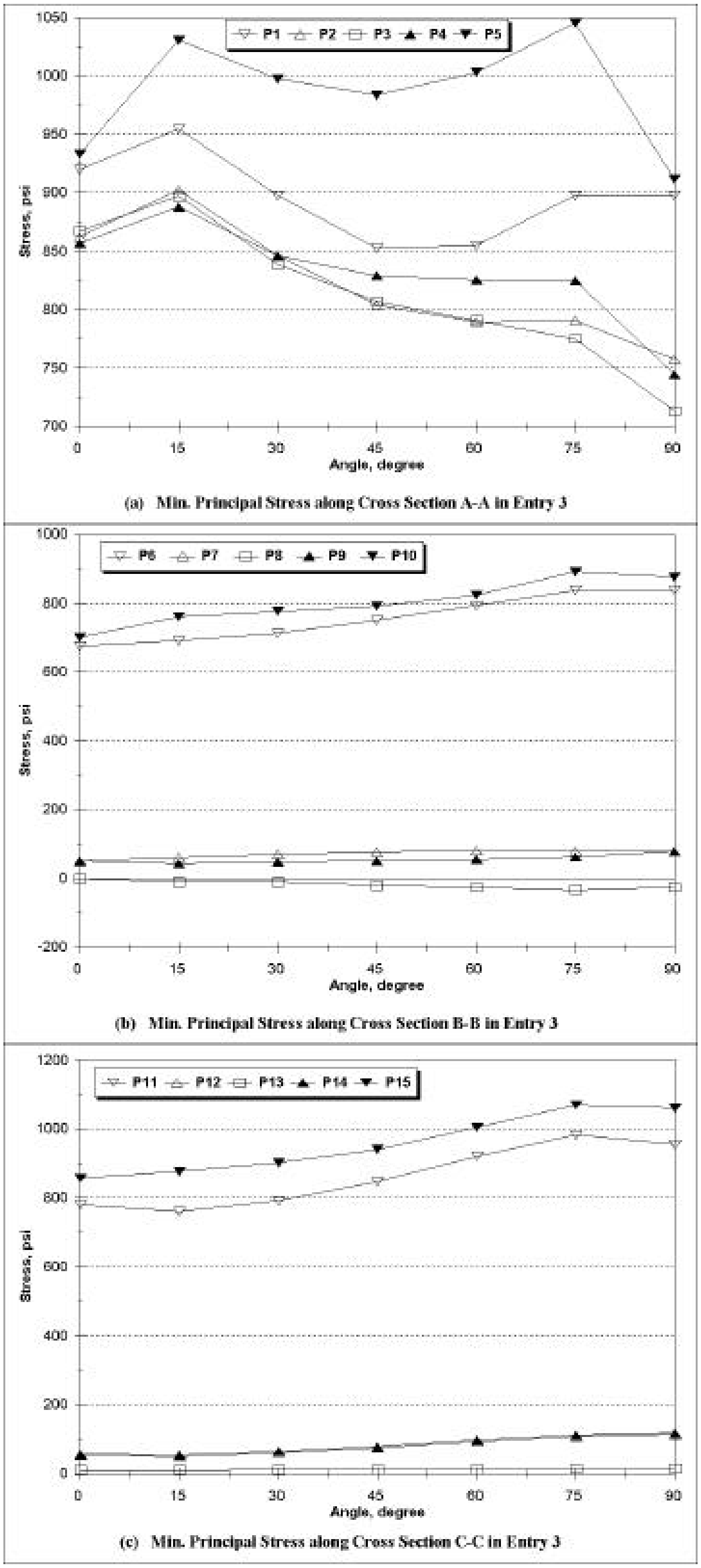
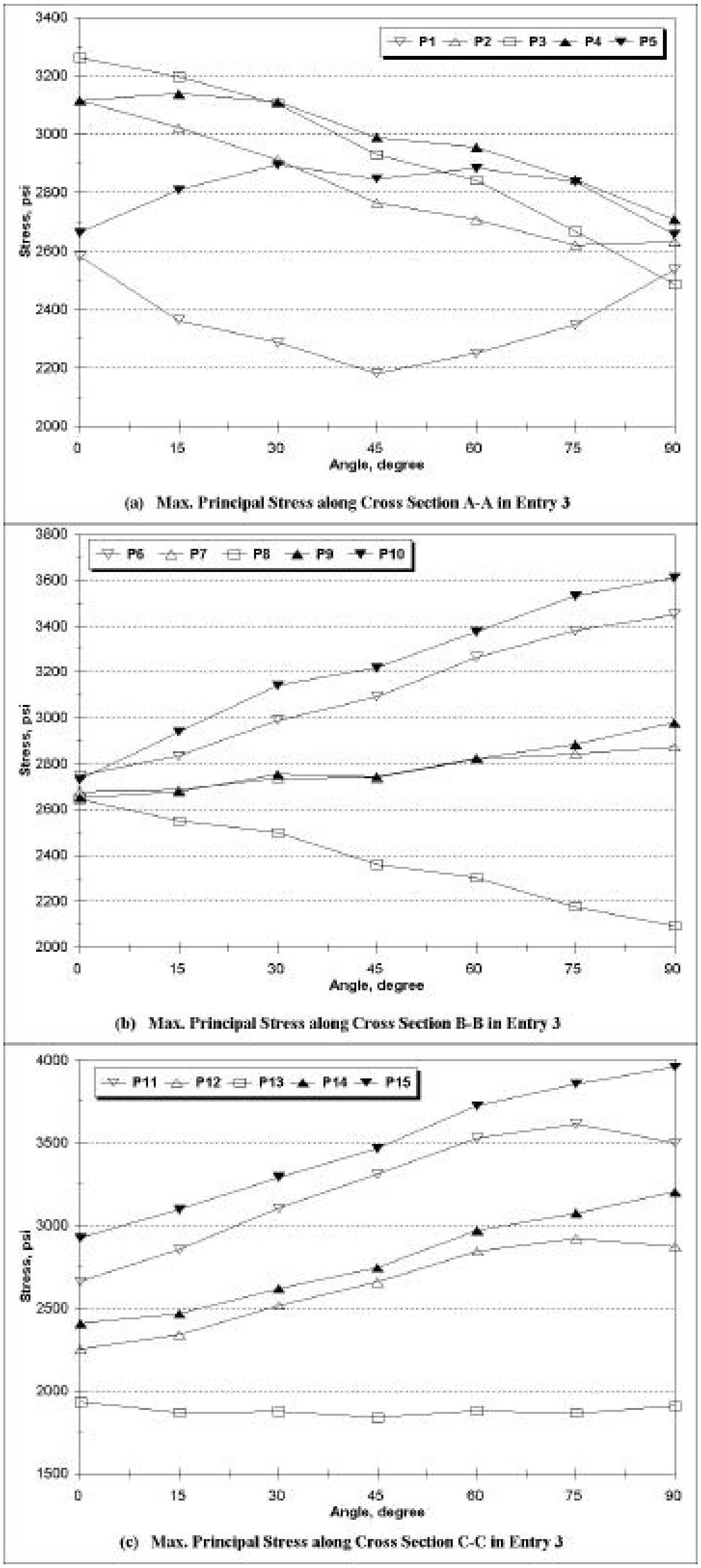


Fig. 4-16 Min. Principal Stress Change with the Angle in Different Cross Sections of Entry 3



(a) Max. Principal Stress along Cross Section A-A in Entry 3

(b) Max. Principal Stress along Cross Section B-B in Entry 3

(c) Max. Principal Stress along Cross Section C-C in Entry 3

Fig. 4-17 Max. Principal Stress Change with the Angle in Different Cross Sections of Entry 3

Based on the above stress analysis, it is found that under the high horizontal stress, the stress concentrations at the rib sides of each entry in a 3-entry system occur at the roof line level. In addition, the stress angle between the entry development direction and the maximum horizontal stress has a significant influence on the roof stresses during a 3-entry system development. Tables 4-2, 4-3, and 4-4 list the Von-Mises stress and the maximum and minimum principal stresses at points P1~P15 in Entries 1, 2, and 3.

In short, the stress angle has a significant effect on the stress distributions in the roof line level of entry 1. Under the high horizontal stress, the Von-Mises stress and the maximum principal stress are concentrated at the two rib sides. When the maximum horizontal stress is from the solid side of entry 1, the stresses at this rib side are larger than those at the other side (near entry 2). The Von-Mises and maximum principal stresses increase with the angle from 0^0 to 60^0, and then decrease from 60^0 to 90^0. They reach the maximum when the angle is about 60^0.

In entry 2, the Von-Mises and maximum principal stresses are concentrated at the two rib sides at the roof line level. The stresses at the rib side near entry 3 are larger than those at the other side. But the difference between them is small. The Von-Mises stress increases with the angle from 0^0 to 60^0, and then slightly decreases. The maximum principal stress also increases rapidly with the angle 0^0 to 60^0, and then increases slightly from 60^0 to 90^0. In entry 2, the stress at the entry face (cross section A-A) is smaller than that in the other cross sections.

In entry 3, the stress in the side near entry 2 increases with the stress angle when the angle is equal to or larger than 45^0. When the angle is equal to 90^0, it reaches the maximum. In all other parts, the angle influence on the roof stress distribution is not significant.

Under a high horizontal stress, the minimum principal stress in the immediate roof is increased, especially at the roof center. Without the horizontal stress, the roof at the entry center is generally in tension, but it is in compression under a high horizontal stress. However, the tensile stress still appears in the roof near the pillar ribs, although it is smaller than that without the horizontal stress. The stress angle effects on the tensile stress distribution are very small, and can be ignored.

Table 4-2 Stresses at Points for Different Angles in Entry 1

Points	No Lateral Stress	Angle (degree) 0	15	30	45	60	75	90
		Von Mises Stress (psi)						
P1	658	1489	1379	1440	1490	1610	1679	1584
P2	772	1901	2077	2139	2103	1895	1771	1671
P3	1003	2092	2289	2332	2252	1847	1650	1556
P4	776	1908	2151	2264	2246	1917	1700	1604
P5	650	1410	1759	2068	2172	1896	1711	1604
P6	1160	1726	1963	2260	2549	2801	2745	2439
P7	808	2187	2410	2589	2753	2850	2782	2502
P8	539	2205	2384	2421	2379	2134	1992	1879
P9	788	2182	2343	2449	2532	2578	2558	2413
P10	1113	1717	1855	2043	2213	2426	2453	2315
P11	1390	1748	1892	2239	2553	2939	2837	2676
P12	840	1981	2073	2334	2589	2954	2856	2694
P13	281	1561	1653	1717	1732	1803	1714	1617
P14	806	1864	1974	2132	2309	2612	2538	2394
P15	1335	1621	1762	1965	2187	2536	2462	2322
		Minimum Principal Stress (psi)						
P1	295	933	971	865	828	851	951	912
P2	335	857	908	826	788	784	782	744
P3	347	867	922	863	823	803	756	713
P4	338	863	911	876	853	832	799	758
P5	300	920	978	928	926	961	969	898
P6	259	701	738	775	810	865	935	876
P7	-156	50	64	83	92	98	94	80
P8	-170	0	-7	-10	-17	-22	-29	-25
P9	-155	51	42	40	43	51	62	79
P10	251	675	665	667	690	725	784	837
P11	359	858	838	887	949	1024	1091	1061
P12	-200	57	48	63	80	101	117	118
P13	-253	11	10	12	13	14	15	16
P14	-207	54	45	60	77	96	110	114
P15	331	780	769	800	846	899	954	955
		Maximum Principal Stress (psi)						
P1	994	2665	2524	2478	2471	2517	2597	2658
P2	1154	3119	3233	3198	3086	2979	2804	2710
P3	1358	3265	3412	3399	3253	3094	2730	2488
P4	1158	3117	3319	3385	3297	3188	2853	2633
P5	993	2583	2853	3090	3131	3122	2817	2535
P6	1530	2731	3028	3349	3565	3752	3802	3610
P7	753	2651	2863	3056	3144	3215	3145	2978
P8	431	2647	2724	2737	2622	2506	2235	2093
P9	733	2678	2728	2837	2856	2884	2816	2874
P10	1474	2748	2778	3011	3159	3288	3335	3450
P11	1833	2925	3038	3448	3708	3958	4049	3958
P12	750	2408	2444	2749	2949	3172	3251	3202
P13	68	1935	1901	1942	1927	1966	1933	1911
P14	707	2253	2306	2507	2649	2814	2888	2873
P15	1751	2663	2784	3060	3252	3435	3526	3499

Table 4-3 Stresses at Points for Different Angles in Entry 2

Points	No Lateral Stress	Angle (degree)						
		0	15	30	45	60	75	90
		Von Mises Stress (psi)						
P1	647	1476	1369	1313	1323	1462	1555	1467
P2	776	1988	2050	1997	1901	1747	1748	1649
P3	1005	2203	2261	2196	2079	1765	1709	1613
P4	776	1988	2131	2151	2104	1863	1748	1649
P5	647	1476	1794	2007	2056	1813	1555	1467
P6	1115	1740	1899	2091	2261	2470	2471	2350
P7	792	2226	2365	2446	2532	2609	2601	2482
P8	543	2288	2372	2328	2252	2091	2070	1953
P9	792	2226	2401	2491	2575	2641	2631	2482
P10	1359	1668	1917	2182	2429	2727	2598	2451
P11	1359	1668	1847	2080	2317	2675	2598	2451
P12	822	1890	2058	2229	2417	2733	2666	2515
P13	281	1528	1699	1732	1717	1766	1659	1565
P14	822	1890	2100	2292	2487	2765	2666	2515
P15	1115	1740	1958	2169	2355	2532	2491	2350
		Minimum Principal Stress (psi)						
P1	307	933	957	933	916	905	930	939
P2	344	890	913	885	841	808	800	812
P3	356	906	931	892	828	792	774	788
P4	344	890	926	907	863	837	819	812
P5	307	933	999	956	963	996	1006	939
P6	253	672	696	726	767	817	851	869
P7	-152	47	40	36	41	52	64	80
P8	-166	-2	-7	-15	-18	-28	-31	-26
P9	-152	47	64	76	81	86	82	80
P10	253	672	722	762	797	846	866	869
P11	348	817	816	855	910	980	1040	1054
P12	-201	49	48	61	79	98	112	116
P13	-250	11	11	12	13	15	15	16
P14	-201	49	47	60	78	98	113	116
P15	348	817	819	861	918	985	1040	1054
		Maximum Principal Stress (psi)						
P1	995	2652	2500	2392	2381	2365	2444	2623
P2	1166	3218	3204	3093	2933	2781	2644	2717
P3	1369	3398	3396	3292	3097	2879	2634	2545
P4	1166	3218	3322	3308	3181	3024	2810	2717
P5	995	2652	2915	3081	3065	2986	2789	2623
P6	1480	2777	2868	3129	3287	3433	3470	3549
P7	740	2725	2754	2828	2848	2885	2867	2946
P8	439	2725	2714	2630	2487	2338	2170	2143
P9	740	2725	2856	2935	2939	2960	2905	2946
P10	1480	2777	3011	3232	3351	3469	3476	3549
P11	1794	2792	3058	3351	3542	3726	3784	3756
P12	731	2297	2417	2623	2769	2944	3021	3026
P13	69	1888	1950	1956	1913	1926	1894	1860
P14	731	2297	2483	2694	2835	2995	3048	3026
P15	1794	2792	2953	3252	3454	3659	3749	3756

Table 4-4 Stresses at Points for Different Angles in Entry 3

Points	No Lateral Stress	Angle (degree)						
		0	15	30	45	60	75	90
		Von Mises Stress (psi)						
P1	650	1410	1238	1216	1175	1387	1531	1444
P2	776	1908	1883	1832	1763	1732	1700	1604
P3	1003	2092	2071	2032	1916	1782	1650	1556
P4	772	1901	1953	1987	1936	1890	1771	1671
P5	658	1489	1649	1818	1821	1825	1679	1584
P6	1113	1717	1833	1996	2142	2463	2453	2315
P7	788	2182	2255	2321	2392	2586	2558	2413
P8	539	2205	2215	2193	2131	2082	1992	1879
P9	808	2187	2313	2391	2447	2643	2652	2502
P10	1160	1726	1913	2064	2171	2500	2585	2439
P11	1335	1621	1792	2018	2261	2607	2462	2322
P12	806	1864	1973	2137	2325	2651	2538	2394
P13	281	1561	1612	1648	1645	1741	1714	1617
P14	840	1981	2088	2223	2392	2786	2856	2694
P15	1390	1748	1906	2078	2290	2752	2837	2676
		Minimum Principal Stress (psi)						
P1	300	920	955	898	853	855	898	898
P2	338	863	903	847	804	790	791	758
P3	347	867	897	839	807	791	775	713
P4	335	857	888	847	829	826	825	744
P5	295	933	1031	998	984	1003	1046	912
P6	251	675	691	713	750	793	838	837
P7	-155	51	62	71	77	81	79	79
P8	-170	0	-9	-11	-20	-25	-32	-25
P9	-156	50	43	48	51	56	63	80
P10	259	701	760	776	792	824	892	876
P11	331	780	760	792	847	921	983	955
P12	-207	54	50	61	75	93	107	114
P13	-253	11	11	11	13	14	15	16
P14	-200	57	55	66	79	98	112	118
P15	359	858	876	901	941	1005	1070	1061
		Maximum Principal Stress (psi)						
P1	993	2583	2364	2288	2181	2250	2349	2535
P2	1158	3117	3025	2915	2767	2709	2622	2633
P3	1358	3265	3199	3107	2932	2844	2669	2488
P4	1154	3119	3140	3113	2991	2957	2847	2710
P5	994	2665	2810	2897	2849	2885	2840	2658
P6	1474	2748	2835	2990	3093	3265	3380	3450
P7	733	2678	2688	2738	2740	2819	2844	2874
P8	431	2647	2551	2500	2362	2303	2176	2093
P9	753	2651	2679	2755	2744	2824	2884	2978
P10	1530	2731	2939	3142	3217	3374	3531	3610
P11	1751	2663	2856	3105	3309	3526	3616	3499
P12	707	2253	2341	2517	2660	2844	2922	2873
P13	68	1935	1871	1876	1841	1881	1865	1911
P14	750	2408	2468	2618	2747	2969	3075	3202
P15	1833	2925	3097	3292	3464	3724	3856	3958

4.3.2 Influence of Stress Angle on Roof Stresses in Crosscuts

In this study, the main purpose is to analyze the stress distributions in the immediate roof of entries, not crosscuts. Therefore, the stresses at the roof line level of the crosscuts 1 and 2 are briefly analyzed at some special points in the rib sides of entries, because the stresses at these points are larger and the stress situations at these points can stand for the whole stress distributions in the crosscuts. In addition, since the minimum principal stress is larger than zero along the rib sides, only the change in the Von-Mises and maximum principal stress with the angle are studied.

In this section, the stress angle is different from that in the previous sections. In the previous sections, the stress angle is defined as that between the maximum horizontal stress and the entry development direction. Here, it is the angle between the maximum horizontal stress and the axial direction of crosscuts, as shown in Fig. 4-18. In each crosscut, there are 5 measurement lines, numbered L1~L5. Lines L1 and L5 are on the rib sides and line L3 is at the center of the roof. The distance from line L2 to line L1 (and from L4 to L5) is 1.5 ft. In addition there are three cross sections in each crosscut, cross sections 1-1, 2-2, and 3-3. Cross sections 1-1 and 3-3 are located at the intersections between an entry and a crosscut. Cross section 2-2 is in the middle of crosscut. In each cross section, there are two points that are located in line L1 and line L5, respectively. There are a total of 12 points, numbered P1~P12. The locations of the lines and points are shown in Fig. 4-18. The stresses along these lines and the points will be discussed. The stress situations at these points can represent the stresses in all crosscuts.

<u>Von-Mises Stresses in Crosscuts</u>

The Von-Mises stresses at the roof line level of crosscuts 1 and 2 are shown in Figs. 4-19 and 4-20. They indicate that the Von-Mises stress is concentrated at the rib sides of the crosscuts. The stress angle has a significant influence on the stresses, especially at the rib sides.

a. Von-Mises Stress in Crosscut 1

In crosscut 1, the Von-Mises stress changes in the different cross sections are shown in Fig. 4-21. In the cross section 1-1 the stress at point P1 increases with the angle from 0^0 to 90^0 while the stress at point P2 increase with the angle from 0^0 to 75^0, and then slightly decreases from 75^0 to 90^0, as shown in Fig. 4-21(a). At point P2, the stress nearly keeps unchanged when the angle is from 60^0 to 75^0. At point P1, the stress reaches the maximum when the angle is about 90^0. At point P2 the stress reaches the maximum when the angle is 75^0. The stresses at points P1 and P2 are not the same. When the angle is less than 45^0, the stress at point P1 is larger than that at point P2. When the angle is equal to or larger than 45^0, the stress at point P2 is larger than that at point P1.

In the cross section 2-2, the Von-Mises stresses at points P3 and P4 increase with the angle from 0^0 to 75^0, and then slightly decrease from 75^0 to 90^0, as shown in Fig. 4-21(b). Although the stress at point P3 is different from that at point P4, the difference between them can be ignored.

The stress in the cross section 3-3 is shown in Fig. 4-21(c). It is similar to that in the cross section 1-1. The difference is that when the angle is less than 45^0, the stress at point P6 is larger than that at point P5. When the angle is equal to or larger than 45^0, the stress at point P5 is larger than that at point P6. At point P5, the stress reaches the maximum when the angle is from 60^0 to 75^0. At the point P6, it is the maximum when the angle is 90^0.

Fig. 4-21 indicates that the stress at the cross section 3-3 is the largest in these three cross sections. The stress at cross section 1-1 is larger than that at the cross section 2-2.

b. Von-Mises Stress in Crosscut 2

In crosscut 2, the Von-Mises stress is similar to that in crosscut 1, as shown in Fig. 4-22. In the cross section 1-1, the stress at point P7 increases with the angle from 0^0 to 90^0. The stress at point P8 increases rapidly with the angle from 0^0 to 60^0, then slightly increases from 60^0 to 75^0, and finally decreases slightly from 75^0 to 90^0, as shown in Fig. 4-22(a). When the angle is less than 45^0, the stress at point P7 is larger than that at point P8. But the stress at point P8 is larger when the angle is equal to or larger than 45^0.

In the cross section 2-2, the Von-Mises stresses at point P9 and P10 increase with the angle from 0^0 to 75^0, and then decrease slightly from 75^0 to 90^0, as shown in Fig. 4-

22(b). In addition, when the angle is less than 45^0, the stress at point P9 is larger than that at point P10. The stress at point P10 is larger when the angle is equal to or larger than 45^0. But the difference of stresses between at P9 and at P10 is small.

The Von-Mises stresses at point P11 and P12 in the cross section 3-3 increase with the angle from 0^0 to 75^0, and then decrease slightly from 75^0 to 90^0, as shown in Fig. 4-22(c). When the angle is less than 45^0, the stress at point P12 is larger than that at point P11. The stress at point P11 is larger when the angle is equal to or larger than 45^0.

Based on the above analysis, it is found that the Von-Mises stress at the roof line level in the crosscuts increases with the angle from 0^0 to 75^0. When the angle is about 60^0 to 75^0, the stress reaches the maximum. In addition, in each cross section, the stress at one rib side is larger than that at the other side when the angle is less than 45^0. When the angle is equal to or larger than 45^0, the reverse is true.

Maximum Principal Stress in Crosscuts

a. Max. Principal Stress in Crosscut 1

The maximum principal stresses at the rib sides in crosscut 1 are shown in Fig. 4-23. In the cross section 1-1 (Fig. 4-23(a)), the stress at points P1 increases rapidly with the angle form 0^0 to 60^0, then increases slightly from 60^0 to 75^0, and finally decreases slightly form 75^0 to 90^0. At point P2, the stress increases with the angle from 0^0 to 90^0. The stress at point P1 is larger than that at point P2.

In the cross section 2-2, the stresses at the rib sides increase with the angle from 0^0 to 75^0, and then decrease slightly from 75^0 to 90^0, as shown in Fig. 4-23(b).

In the cross section 3-3, the stresses increase with the angle from 0^0 to 75^0, and then decrease slightly from 75^0 to 90^0, as shown in Fig. 4-23(c). The stress at point P5 is larger than that at point P6.

In each cross section of crosscut 1, the maximum principal stress at one point is always larger than that at the other point. This pattern does not change with the angle.

Table 4-5 lists the Von-Mises stress and the maximum principal stress at points P1 ~ P12 in Crosscut 1 and 2.

b. Max. Principal Stress in Crosscut 2

The maximum principal stress at the rib sides of crosscut 2 is shown in Fig. 4-24. It indicates that the stresses at all points increase with the angle from 0^0 to 75^0, and then decrease slightly from 75^0 to 90^0. At each cross section, the maximum principal stress at one point is always larger than that at the other point.

Based on the above analysis, it is confirmed that the stress angle does have a significant influence on the stress in the immediate roof of crosscuts. Generally, when the angle between the maximum horizontal stress and the axial direction of the crosscut is about 60^0 ~75^0, the Von-Mises stress in the roof line level reaches the maximum at the rib sides. In addition, the Von-Mises stress at one rib side in any cross section of the crosscut is larger than that at the other rib side when the angle is less than 45^0. When the angle is equal to or larger than 45^0, the reverse is true. At the corners of the intersection between an entry and a crosscut, the stress increases slowly with the angle from 0^0 to 30^0. Therefore, the angle between the maximum horizontal stress and the axial direction of a crosscut should not exceed 30^0, in order to keep the crosscut in a good condition.

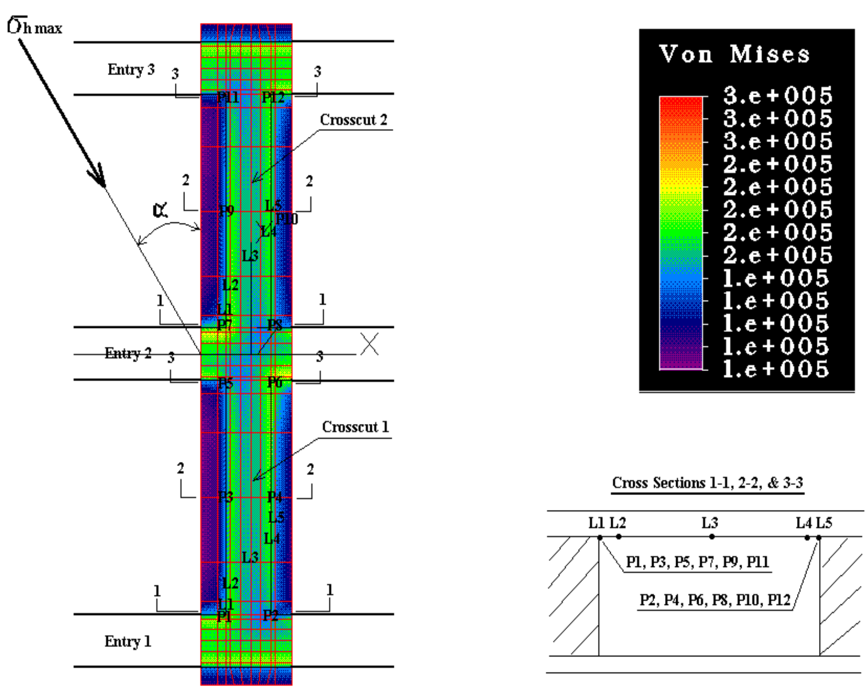


Fig. 4-18 The Locations of Lines, Cross Sections, and Points in Crosscuts 1 and 2

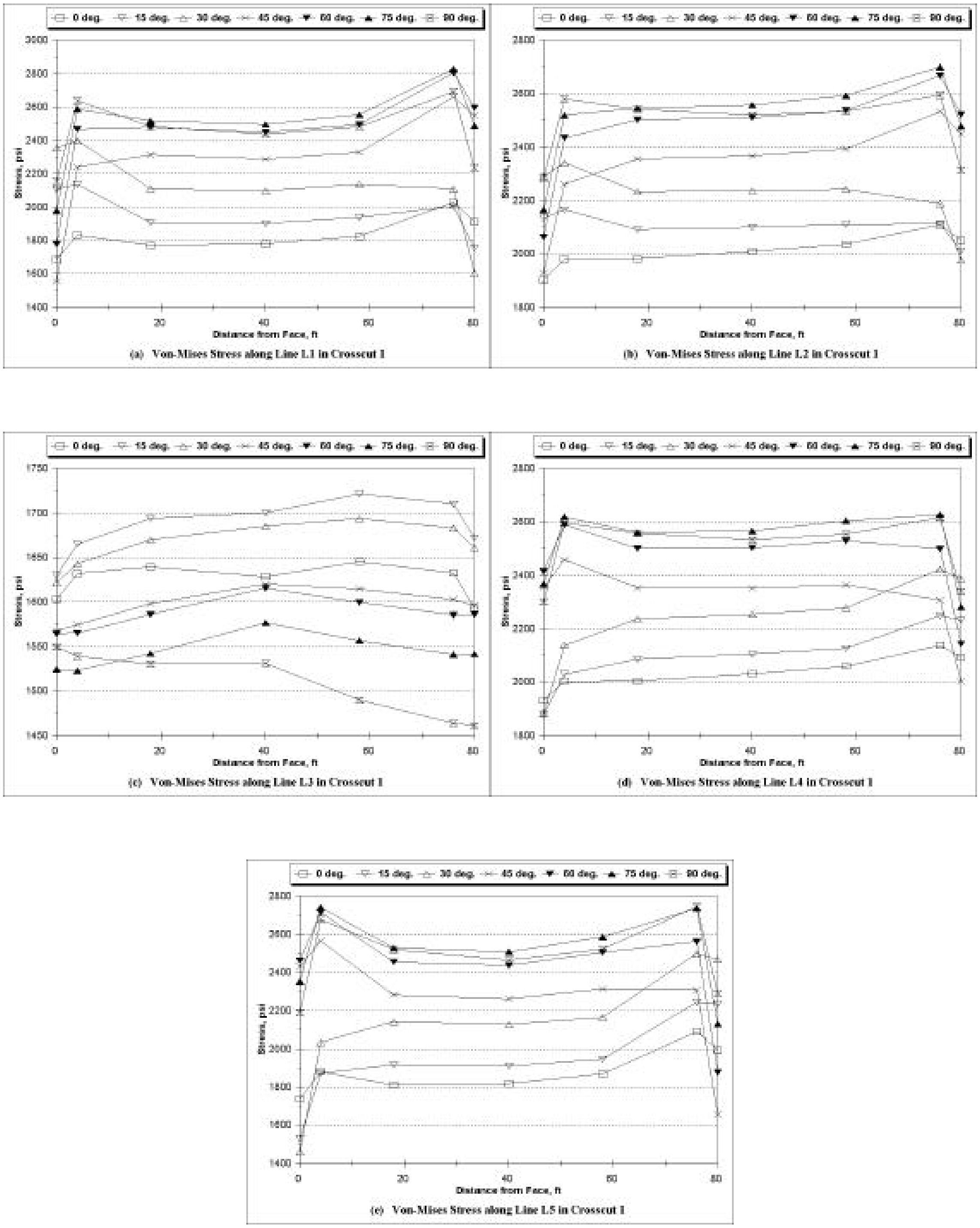
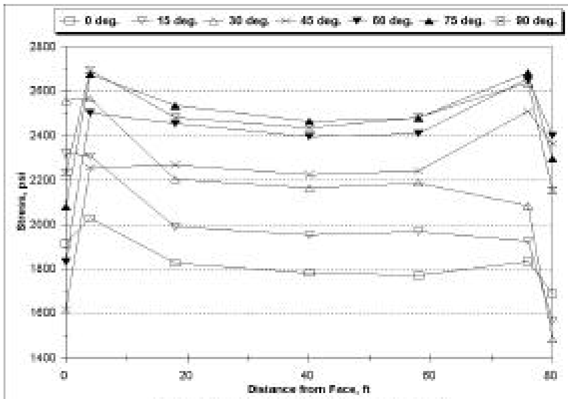
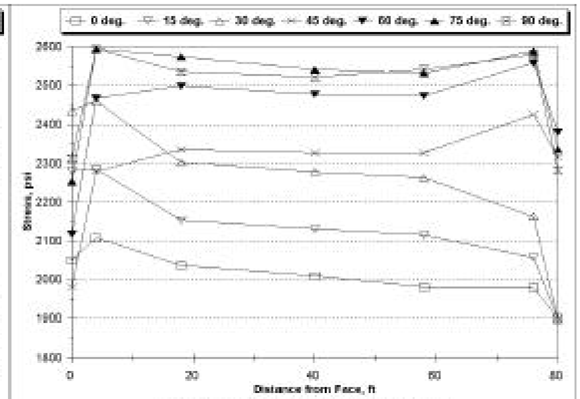


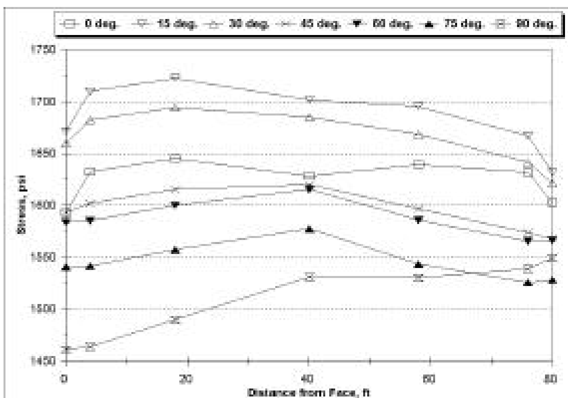
Fig. 4-19 Von-Mises Stress Change with the Angle in Crosscut 1



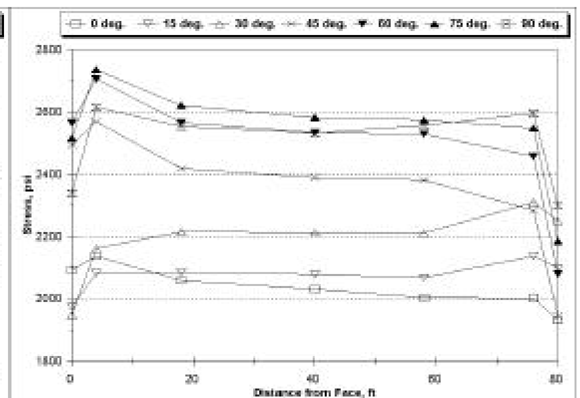
(a) Von-Mises Stress along Line L1 in Crosscut 2



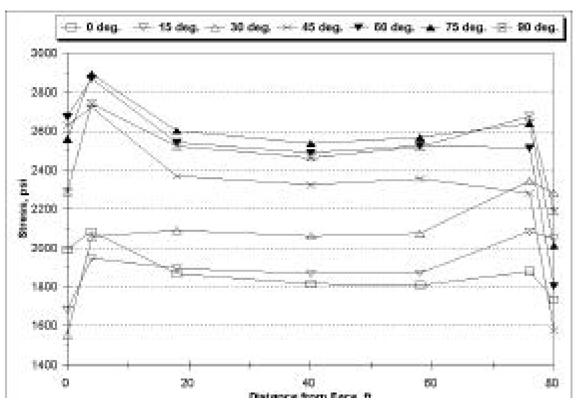
(b) Von-Mises Stress along Line L2 in Crosscut 2



(c) Von-Mises Stress along Line L3 in Crosscut 2

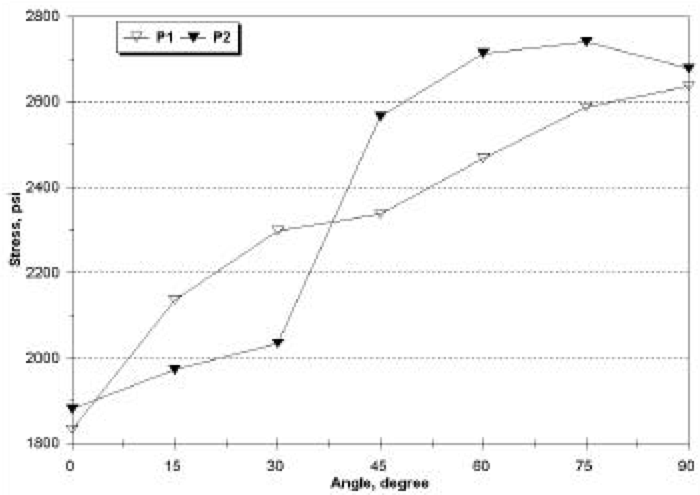


(d) Von-Mises Stress along Line L4 in Crosscut 2

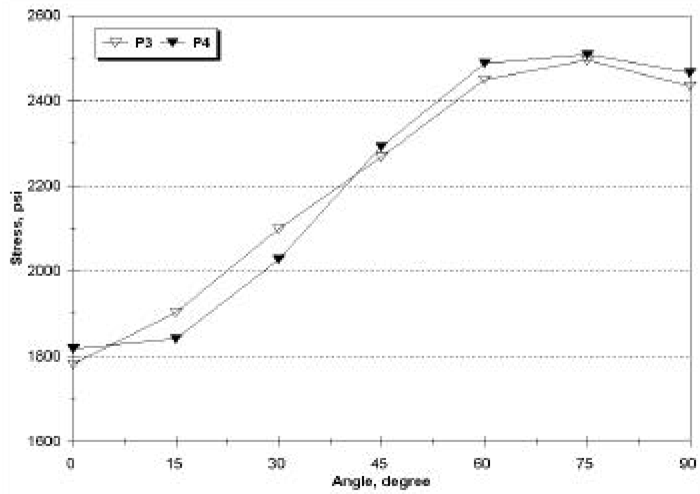


(c) Von-Mises Stress along Line L5 in Crosscut 2

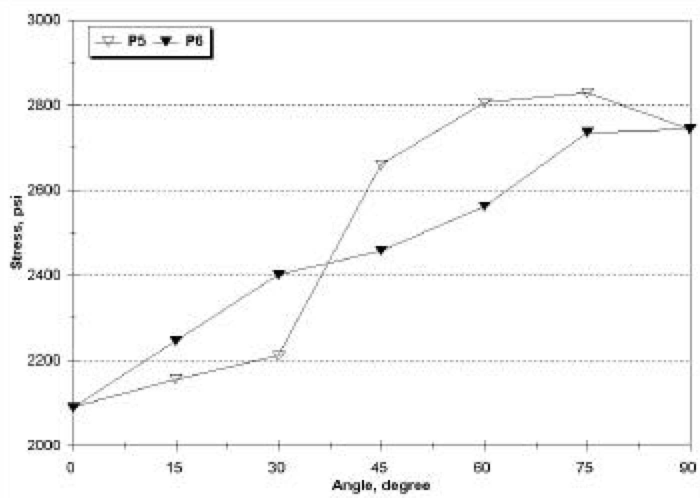
Fig. 4-20 Von-Mises Stress Change with the Angle in Crosscut 2



(a) Von-Mises Stress along Cross Section 1 in Crosscut 1

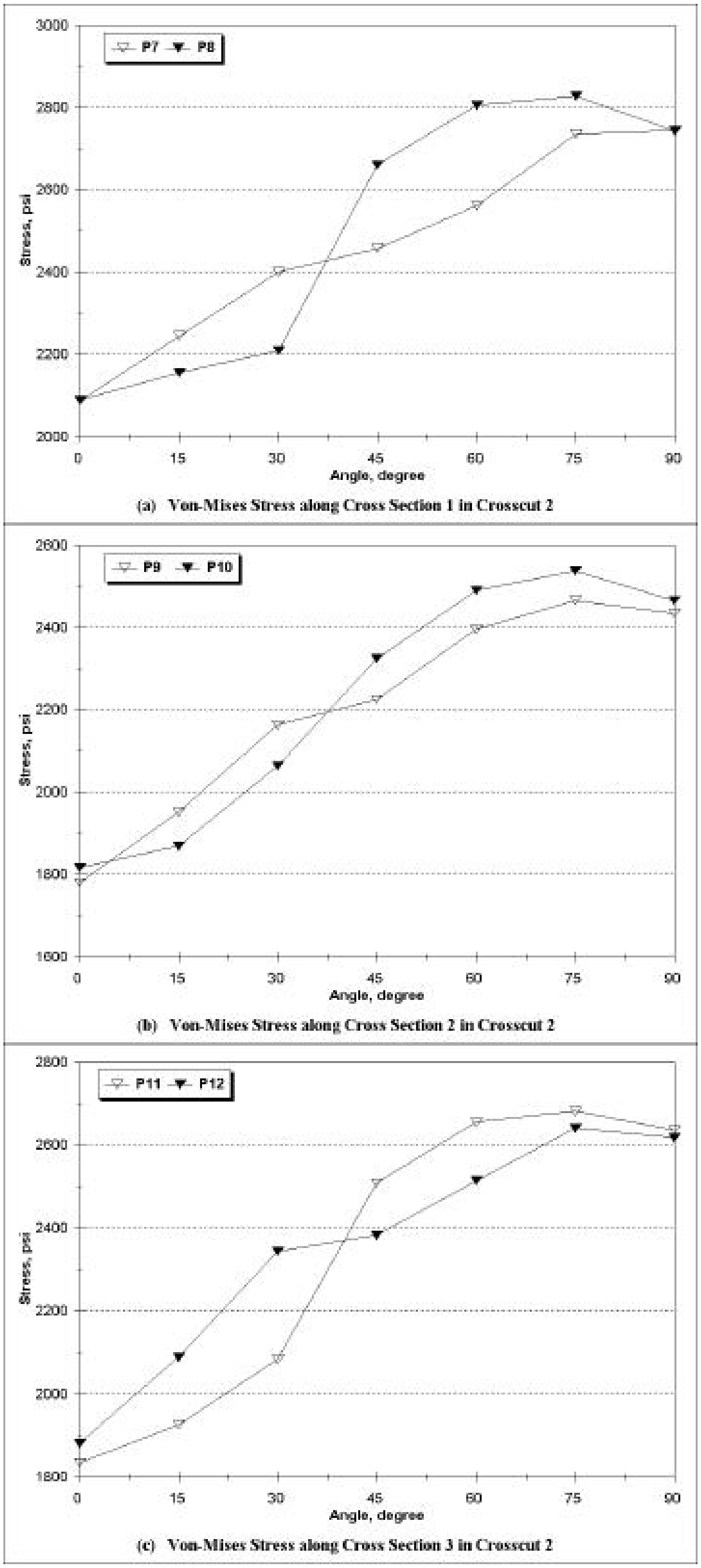


(b) Von-Mises Stress along Cross Section 2 in Crosscut 1



(c) Von-Mises Stress along Cross Section 3 in Crosscut 1

Fig. 4-21 Von-Mises Stress Change with the Angle in Different Cross Sections in Crosscut 1

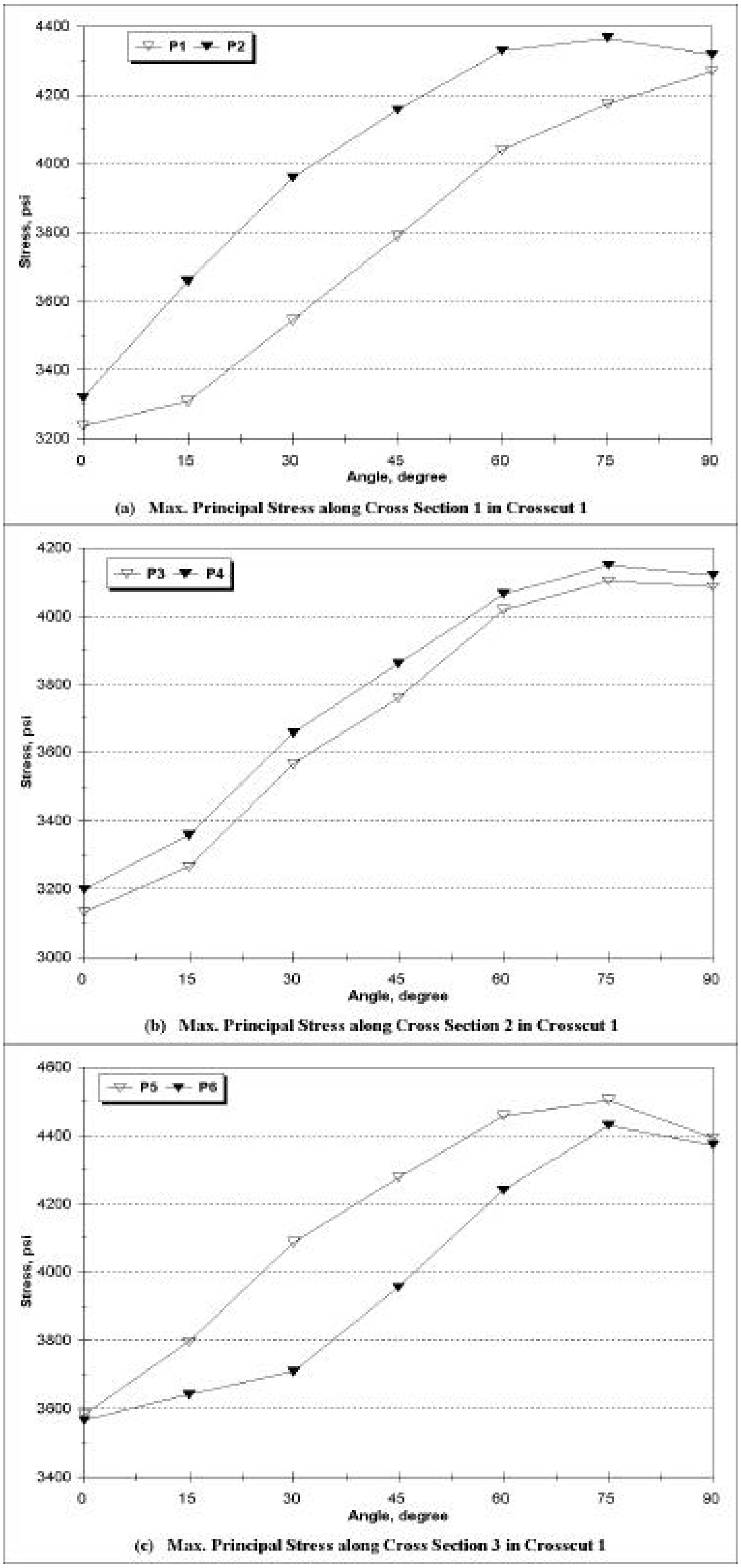


(a) Von-Mises Stress along Cross Section 1 in Crosscut 2

(b) Von-Mises Stress along Cross Section 2 in Crosscut 2

(c) Von-Mises Stress along Cross Section 3 in Crosscut 2

Fig. 4-22 Von-Mises Stress Change with the Angle in Different Cross Sections in Crosscut 2

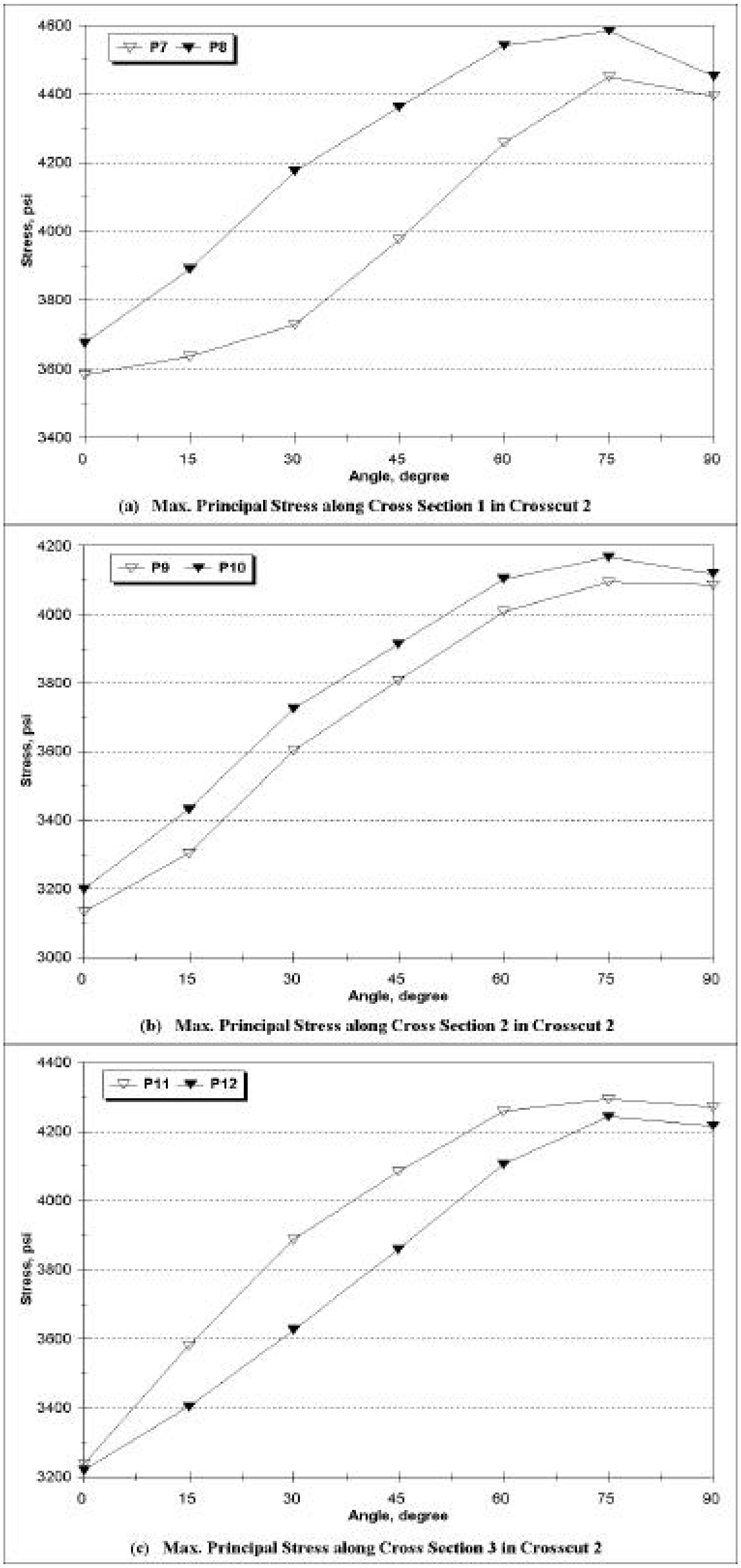


(a) Max. Principal Stress along Cross Section 1 in Crosscut 1

(b) Max. Principal Stress along Cross Section 2 in Crosscut 1

(c) Max. Principal Stress along Cross Section 3 in Crosscut 1

Fig. 4-23 Max. Principal Stress Change with the Angle in Different Cross Sections in Crosscut 1



(a) Max. Principal Stress along Cross Section 1 in Crosscut 2

(b) Max. Principal Stress along Cross Section 2 in Crosscut 2

(c) Max. Principal Stress along Cross Section 3 in Crosscut 2

Fig. 4-24 Max. Principal Stress Change with the Angle in Different Cross Sections in Crosscut 2

Table 4-5 Stresses at Points in Crosscuts 1 and 2

Points	Angle (degree)						
	0	15	30	45	60	75	90
	Von Mises Stress (psi)						
P1	1834	2137	2298	2338	2468	2588	2638
P2	1881	1973	2035	2566	2714	2741	2678
P3	1781	1903	2099	2268	2451	2496	2435
P4	1817	1841	2027	2293	2488	2510	2466
P5	2091	2156	2211	2661	2806	2829	2744
P6	2089	2246	2401	2458	2563	2737	2745
P7	2089	2246	2401	2458	2563	2737	2745
P8	2091	2156	2211	2661	2806	2829	2744
P9	1781	1951	2165	2226	2397	2467	2435
P10	1817	1869	2065	2325	2491	2539	2466
P11	1834	1926	2083	2510	2656	2683	2638
P12	1881	2089	2345	2383	2515	2642	2618
	Maximum Principal Stress (psi)						
P1	3237	3309	3546	3789	4040	4175	4271
P2	3319	3659	3960	4157	4330	4368	4317
P3	3133	3266	3567	3760	4019	4104	4086
P4	3199	3359	3658	3861	4065	4149	4119
P5	3583	3797	4088	4278	4458	4504	4394
P6	3566	3641	3709	3955	4242	4431	4373
P7	3583	3636	3729	3975	4258	4451	4394
P8	3676	3891	4176	4361	4542	4583	4453
P9	3133	3303	3603	3807	4008	4094	4086
P10	3199	3431	3725	3914	4103	4167	4119
P11	3237	3581	3888	4085	4260	4294	4271
P12	3219	3403	3626	3858	4106	4244	4217

4.4 Influence of Stress Ratio on Roof Stress

Field measurements have confirmed that the horizontal stresses are biaxial, with the maximum horizontal stress much greater than the minimum horizontal stress in most cases. The stress ratio of maximum to minimum horizontal stresses ($\boldsymbol{\sigma_{hmax} / \sigma_{hmin}}$) ranges from 1.1 to 1.7 (see Tables 2-1 and 2-2). In the initial study, it has been found that the ratio influence on the maximum and minimum principal stresses is not as significant as that on the Von-Mises stress. Therefore, the influence of the stress ratio on the Von-Mises stress is analyzed in this section, when the ratio is 1.0, 1.2, 1.5, 1.7, 2.0, and 3.0, respectively.

As analyzed in the previous sections, the Von-Mises stress is concentrated at the rib sides of each entry. Generally, the stress in the cross section B-B is larger. Therefore, in the following, the stress change with the stress ratio at one point in the cross section B-B, at which the stress is the largeest, is studied in each entry.

4.4.1 Influence of the Stress Ratio in Entry 1

The Von-Mises stress changes with the stress ratio in entry 1 are shown in Figs. 4-25 and 4-26 and listed in Table 4-6. They indicate that the influence of the stress ratio on the Von-Mises stress at the roof line level depends not only on the ratio values but also on the stress angle between the maximum horizontal stress and the entry development direction. When the angle is less than 45^0, the Von-Mises stress decreases with the ratio from 1.0 to 2.0, then decreases very slightly from 2.0 to 3.0. When the angle is equal to or larger than 45^0, the ratio influence on the stress is very small. When the angle is about $60^0 \sim 75^0$, the Von-Mises stress reaches the maximum in entry 1. In this situation, the stress slightly increases with the ratio. Generally speaking, the influence of the stress ratio on the Von-Mises stress at the roof line level is much smaller than the influence of the stress angle.

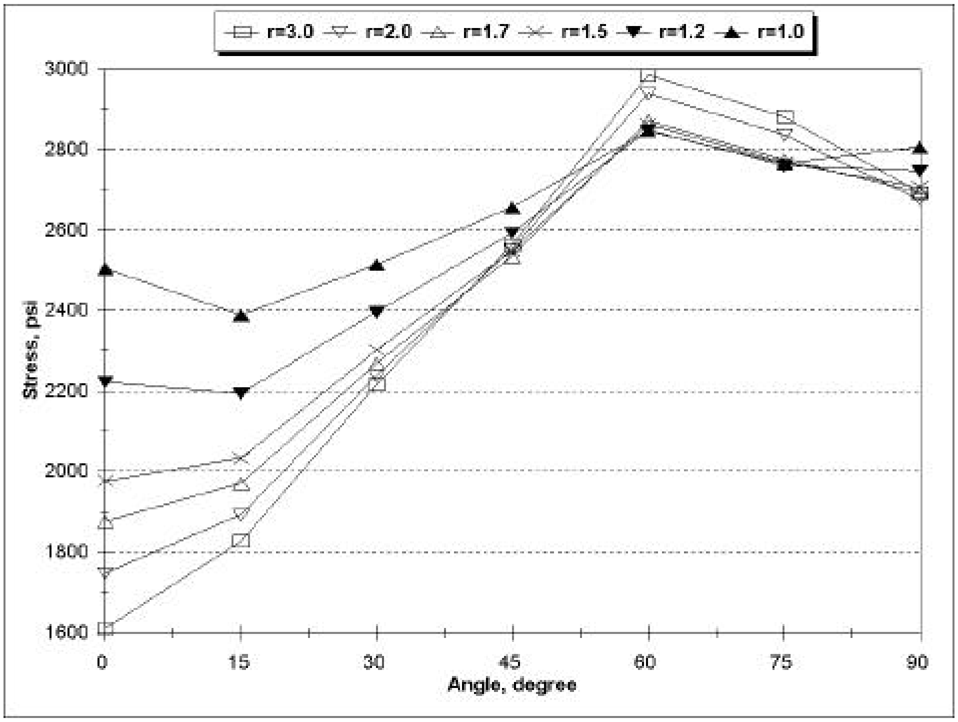


Fig. 4-25 Influence of the Stress Ratio on Von-Mises Stress in Entry 1

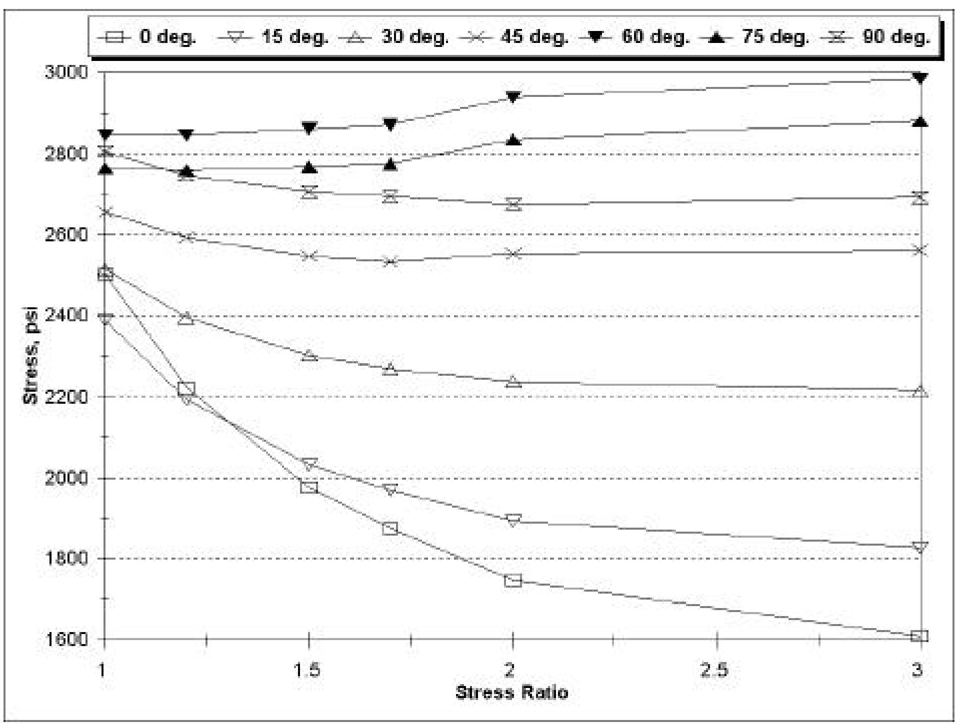


Fig. 4-26 Influence of the Stress Ratio on Von-Mises Stress for Different Angles in Entry 1

Table 4-6 Von-Mises Stress Change with the Ratio in Entry 1

Stress Ratio	Stress Angle (degree)						
	0	15	30	45	60	75	90
3.0	1610	1827	2217	2562	2984	2882	2694
2.0	1748	1892	2239	2553	2939	2837	2676
1.7	1876	1971	2269	2533	2872	2776	2695
1.5	1976	2034	2302	2548	2862	2768	2707
1.2	2223	2195	2395	2593	2849	2761	2747
1.0	2504	2389	2514	2657	2848	2765	2807

4.4.2 Influence of the Stress Ratio in Entry 2

The stress ratio has an influence on the Von-Mises stress at the rib sides in entry 2, as shown in Figs. 4-27 and 4-28. When the angle is equal to or less than 45^0, the Von-Mises stress in entry 2 decreases with the ratio from 1.0 to 3.0. When the angle is larger than 45^0, the influence of the stress ratio is smaller. However, when the angle is about $60^0 \sim 75^0$, the Von-Mises stress increases slightly with the ratio from 1.0 to 3.0. Table 4-7 lists the Von-Mises stresses at the different angles for the different ratios.

Table 4-7 Von-Mises Stress Change with the Ratio in Entry 2

Stress Ratio	Stress Angle (degree)						
	0	15	30	45	60	75	90
3.0	1603	1890	2148	2364	2571	2531	2365
2.0	1740	1958	2169	2355	2532	2491	2350
1.7	1868	2039	2198	2337	2474	2438	2367
1.5	1968	2104	2231	2351	2465	2431	2377
1.2	2213	2271	2321	2393	2454	2424	2412
1.0	2493	2472	2436	2452	2453	2428	2465

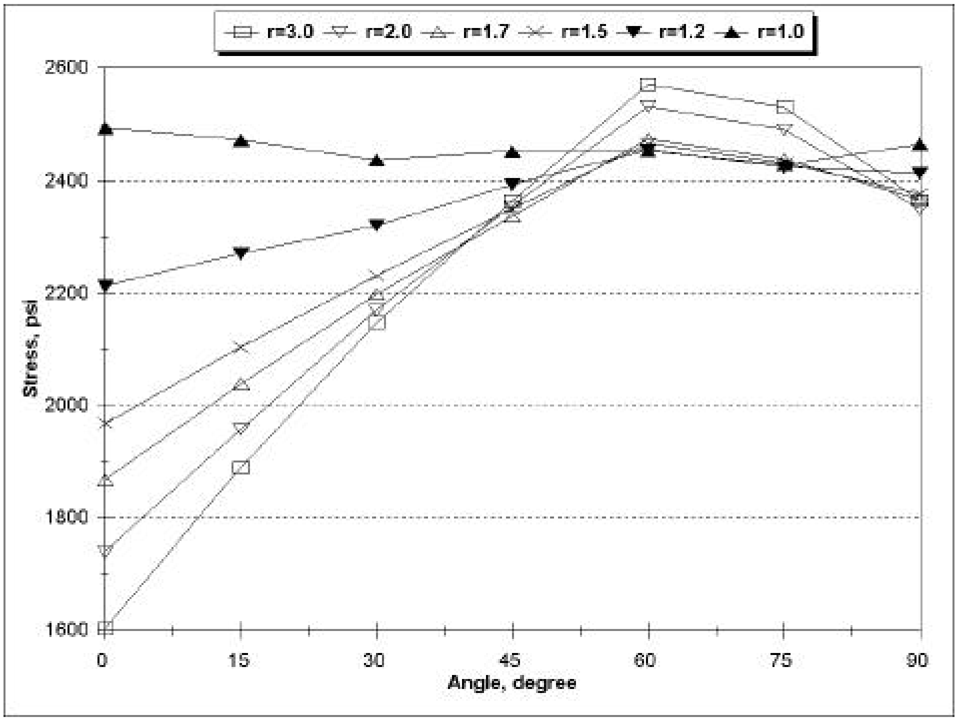


Fig. 4-27 Influence of the Stress Ratio on Von-Mises Stress in Entry 2

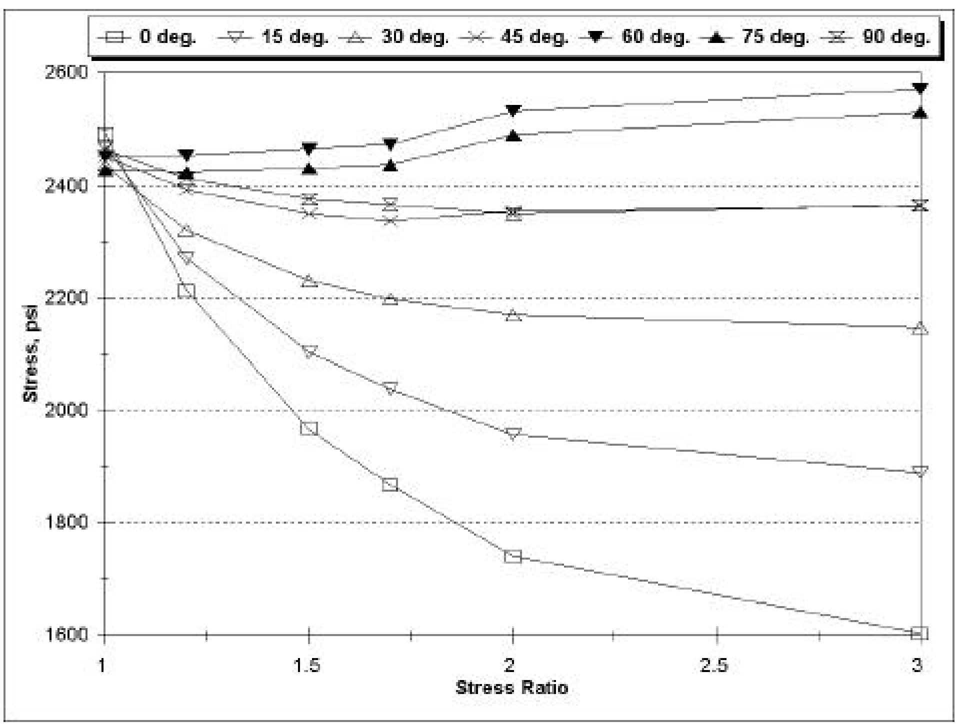


Fig. 4-28 Influence of the Stress Ratio on Von-Mises Stress for Different Angles in Entry 2

4.4.3 Influence of the Stress Ratio in Entry 3

In entry 3, the influence of the stress ratio on the Von-Mises stress is similar to that in entry 1, as shown in Figs. 4-29 and 4-30 and Table 4-8. When the stress angle is equal to or less than 45^0, the Von-Mises stress decreases with the stress ratio from 1.0 to 3.0. When the angle is larger than 45^0, the Von-Mises stress changes very slightly with the ratio.

Table 4-8 Von-Mises Stress Change with the Ratio in Entry 3

Stress Ratio	Stress Angle (degree)						
	0	**15**	**30**	**45**	**60**	**75**	**90**
3.0	1610	1840	2201	2414	2794	2882	2654
2.0	1748	1906	2223	2405	2752	2837	2676
1.7	1876	1985	2253	2387	2689	2776	2695
1.5	1976	2048	2286	2400	2679	2768	2707
1.2	2223	2211	2378	2443	2667	2761	2727
1.0	2504	2407	2496	2503	2666	2765	2707

Based on the above analysis, it is found that the stress ratio has some influence on the Von-Mises stress distributions at the rib sides in the roof line level during a 3-entry development. Generally, the influences of the stress ratio on the Von-Mises stress in the three entries are the same. The influence of the stress ratio depends not only on the ratio values but also on the stress angle between the maximum horizontal stress and the entry development direction. When the angle is less than 45^0, the Von-Mises stress decreases apparently with the ratio from 1.0 to 2.0. When the ratio is from 2.0 to 3.0, the Von-Mises stress decreases very slightly. When the angle is larger than 45^0, the Von-Mises stress hardly changes with the ratio. Since the entry system is in the worst condition when the angle is from 60^0 to 75^0, the influence of the stress ratio on the entry stability can be ignored.

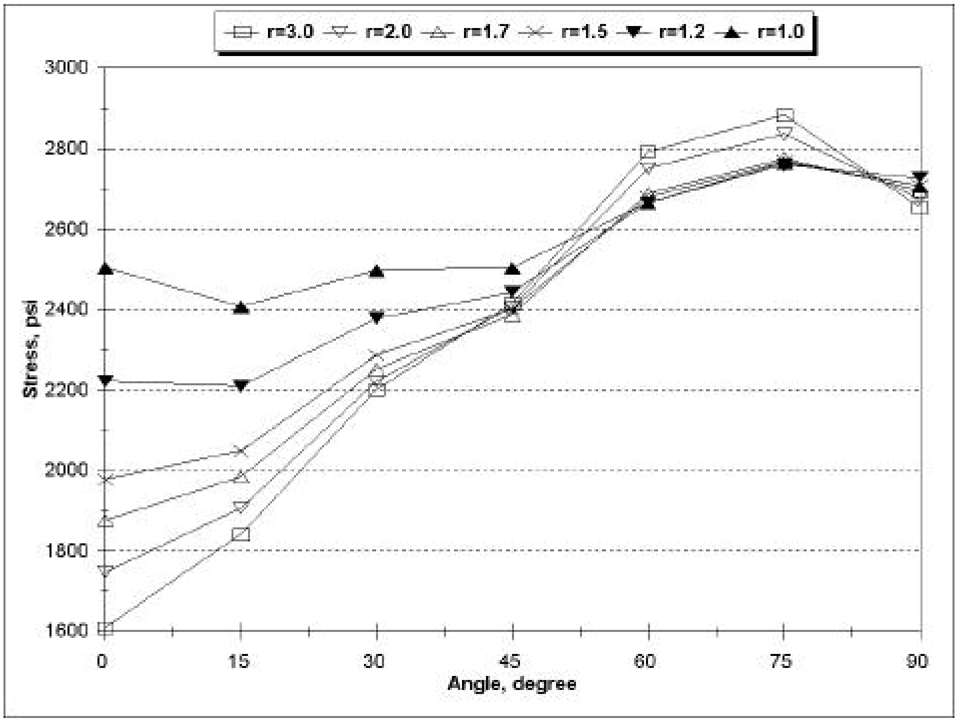


Fig. 4-29 Influence of the Stress Ratio on Von-Mises Stress in Entry 3

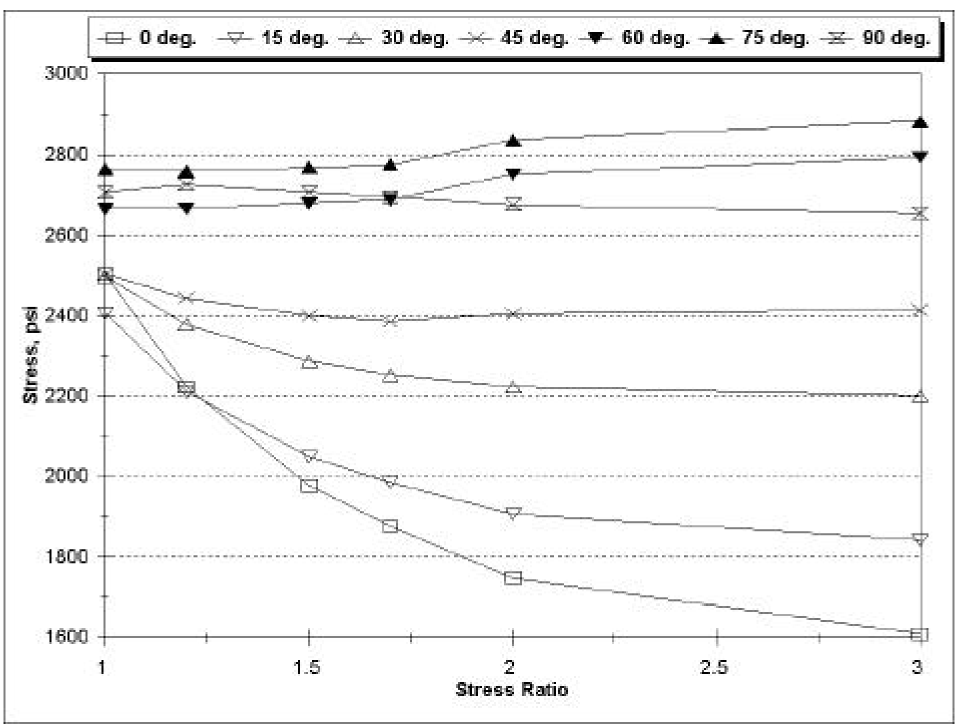


Fig. 4-30 Influence of the Stress Ratio on Von-Mises Stress for Different Angles in Entry 3

4.5 Von-Mises Stress in Higher Horizontal Stress Field

As discussed in the initial study, the magnitude of the horizontal stress is also a factor affecting the roof stability. Generally, the pattern of stress distribution does not change under the higher horizontal stress. The magnitude of stress increases with the horizontal stress. In addition, the minimum principal stress is larger when a higher horizontal stress acts on the entry system. In this case, the tensile stress is very small, even disappeared. The Maximum principal stress also increases in higher horizontal stress field. But its pattern keeps unchanged. Therefore, in this section, only Von-Mises stress change with the different stress angle between the maximum horizontal stress and the entry development direction is studied.

The maximum horizontal stress is 4,500 psi and the minimum horizontal stress is 2,250 psi. The other geological conditions keep the same, namely, weak roof and the overburden depth of 800 ft.

The Von-Mises stress distributions at the roof line level along lines L1~L5 are shown in Fig. 4-31, when the stress angle between the maximum horizontal stress and the entry development direction is 60^0. The patterns of the stress distributions do not change for the different horizontal stresses. In entry 1, the Von-Mises stress is concentrated at the two rib sides, as shown in Fig. 4-31(a). In addition, the stress at the one rib side (lines L1and L2) is larger than that at the other side (L4 and L5). In entry 2, the Von-Mises stress is also concentrated at the two rib sides. The stress at the rib side near entry 3 (lines L4 and L5) is larger than that at the other side (L1, and L2). But the difference between them is small. In entry 3, the Von-Mises stress at the rib side near entry 2 (lines L1 and L2) is less than that at the other side (L4 and L5). However, the difference between them is not as large as that in entry 1.

Fig. 4-32 shows the Von-Mises stresses at the roof line level of the entries under the different horizontal stresses. It indicates that the stress angle is still an important factor affecting the entry roof. When the angle is about 60^0 ~ 75^0, the entry system is in the worst condition. In addition, the pattern of stress distribution is hardly changed in the different horizontal stress fields.

Table 4-9 Von-Mises Stresses for Different Horizontal Stresses

Entry	Max. Horizontal Stress (psi)	Stress Angle (degree)						
		0	15	30	45	60	75	90
1	3,000	1748	1892	2239	2553	2939	2837	2676
	4,500	2837	2989	3325	3625	4150	3987	3685
2	3,000	1740	1958	2169	2355	2532	2491	2350
	4,500	2870	3045	3245	3522	3885	3763	3421
3	3,000	1748	1906	2223	2405	2752	2837	2676
	4,500	2868	3050	3334	3455	3815	3830	3479

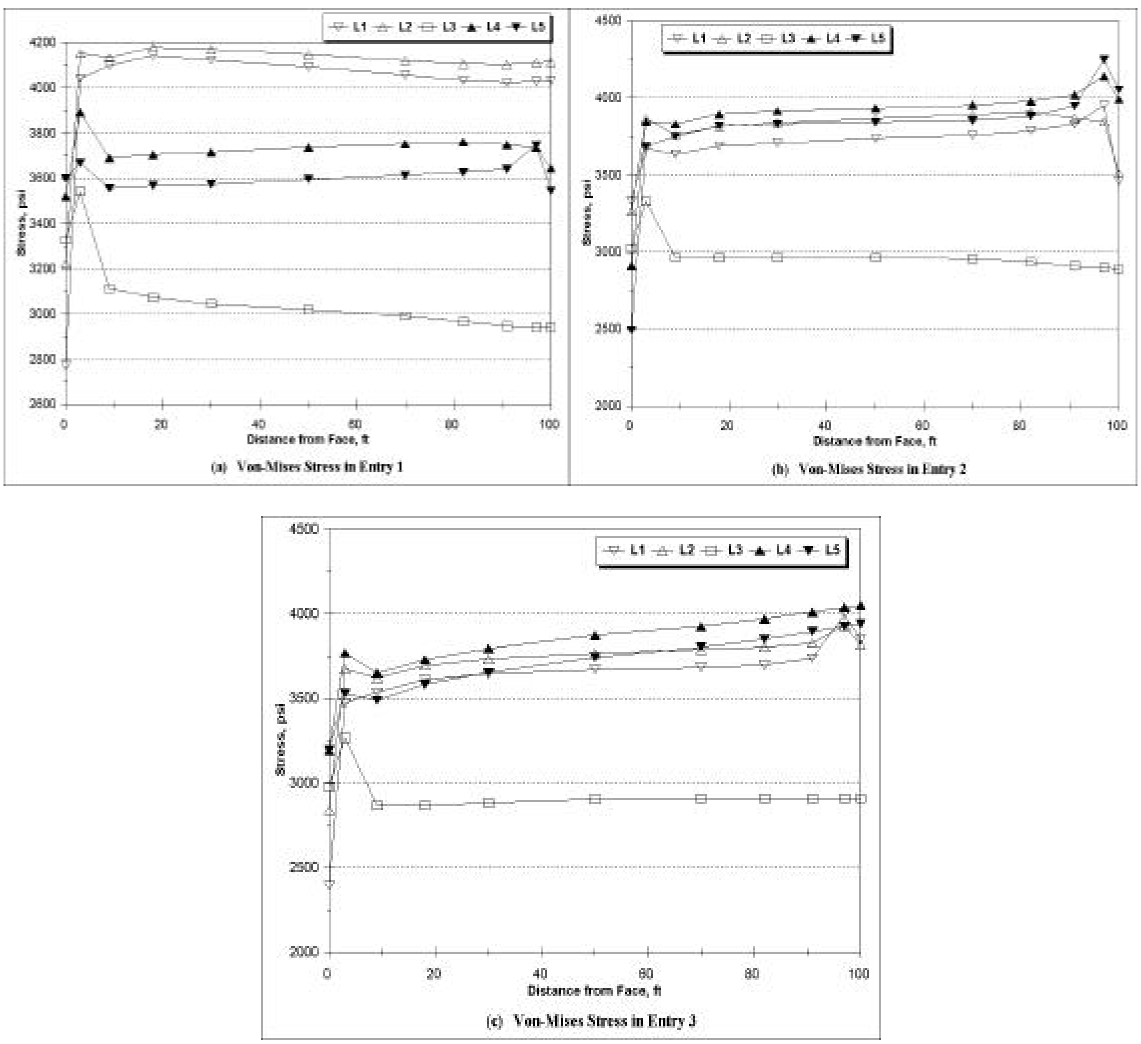


Fig. 4-31 Von-Mises Stress Distribution in Entries ($\sigma_{h\ max}$ = 4,500 psi)

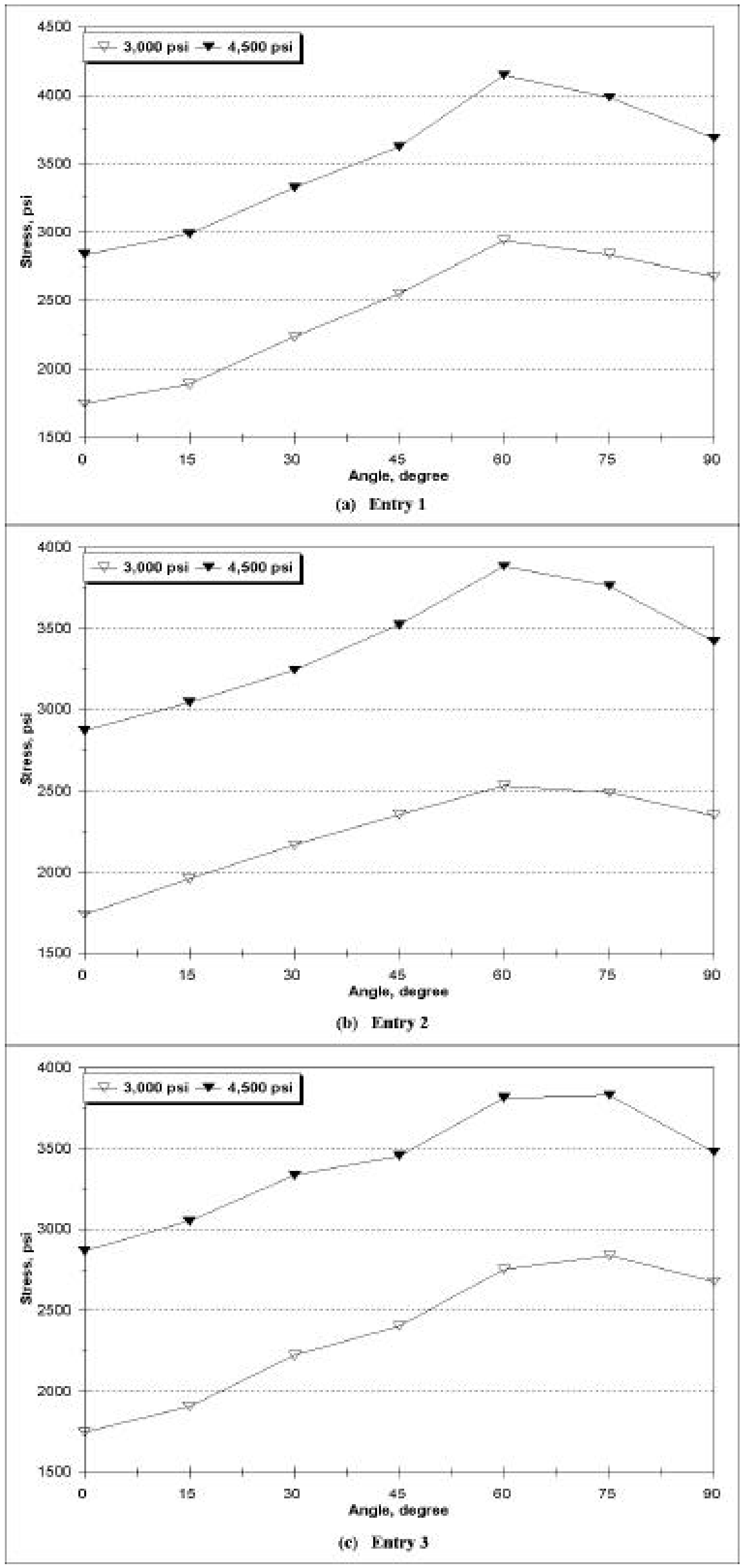


Fig. 4-32 Von-Mises Stress in Entries for Different Horizontal Stresses

4.6 Stress in Medium Immediate Roof

Based on the initial study, it has been found that the pattern of stress distributions in the immediate roof does not change with the roof type, but the magnitude of the stress does change. Generally, the stress in the weak roof is smaller than that in the medium strength roof.

Fig. 4-33 shows the Von-Mises stresses in the different types of roof. In the three-entry system, the stress pattern does not change with the roof properties. In the medium strength roof, the Von-Mises stress also increases with the stress angle between the maximum horizontal stress and the entry development direction and is concentrated at the rib sides. In entry 1, the Von-Mises stress increases with the angle from 0^0 to 60^0, and then decreases from 60^0 to 90^0, as shown in Fig. 4-33(a). In entry 1 the stress at the solid rib side is larger than that at the other side. In entry 2, the Von-Mises stress at the rib side near entry 1 is smaller than that that at the other side. But, the difference between them is small in the medium roof. The Von-Mises stress in entry 2 is shown in Fig. 4-33(b). The stress increases with the angle from 0^0 to 60^0, and then decreases slightly from 60^0 to 90^0. In entry 3, the Von-Mises stress at the solid rib side is larger than that at the other side. The Von-Mises stress increases with the angle from 0^0 to 75^0, and then decreases slightly from 75^0 to 90^0. Based on the above stress analysis, it is found that a three-entry system is in the worst condition when the angle is about 60^0 ~ 75^0.

Under a given condition, the Von-Mises stress in the medium roof increases about 10~20%, as compared to that in the weak roof. Table 4-10 lists the Von-Mises stresses in the weak and medium roofs.

Table 4-10 Von-Mises Stresses in Different types of Roof

Entry	Roof Type	Stress Angle (degree)						
		0	15	30	45	60	75	90
1	weak	1748	1892	2239	2553	2939	2837	2676
	medium	2098	2271	2642	2961	3380	3234	3051
2	weak	1740	1958	2169	2355	2532	2491	2350
	medium	2088	2349	2560	2732	2912	2840	2679
3	weak	1748	1906	2223	2405	2752	2837	2676
	medium	2098	2288	2623	2890	3165	3234	3051

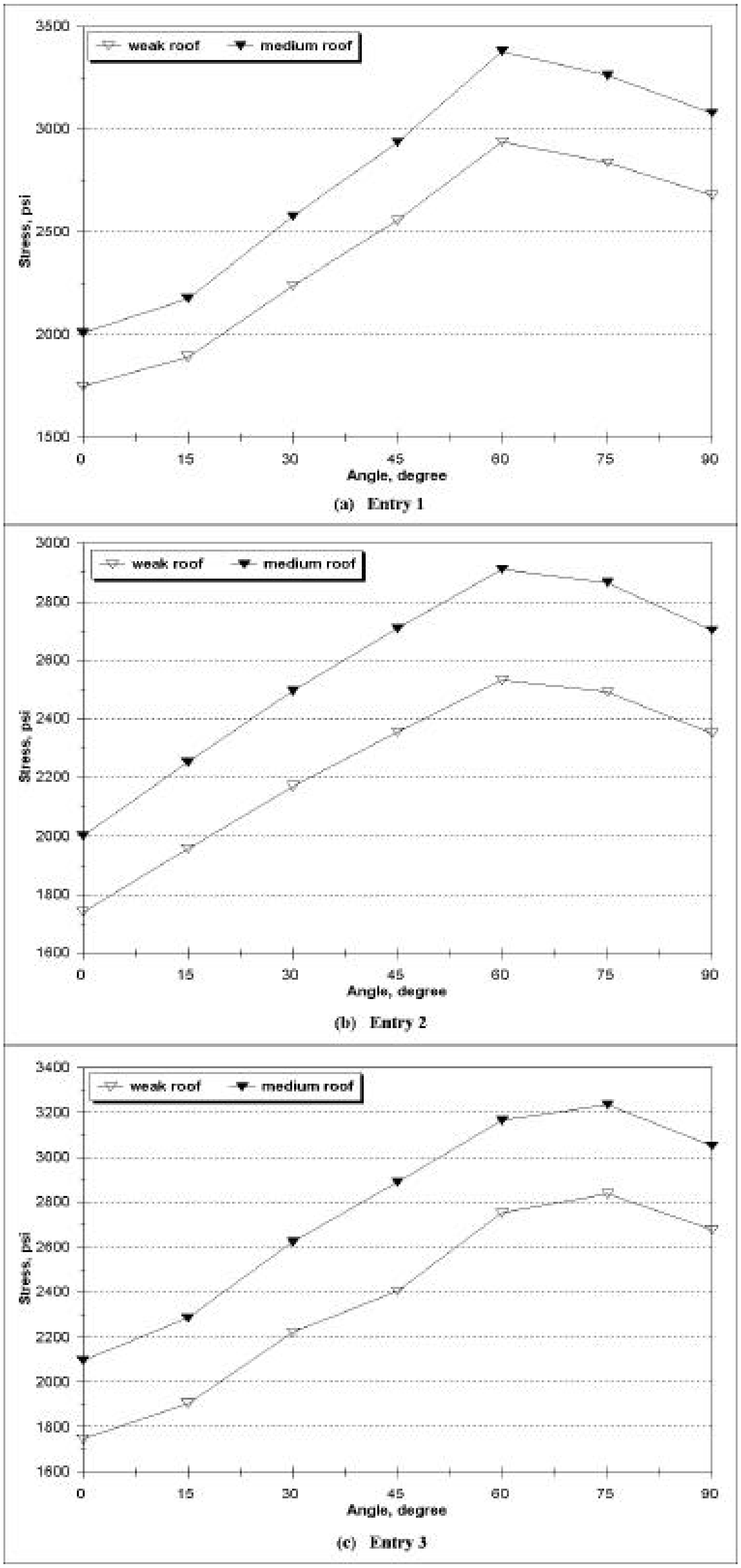


Fig. 4-33 Von-Mises Stress Distributions in Different Types of Roof

4.7 Sequence of Entry Development

In order to determine if the sequence of cutting and mining in an entry development affects the stress distributions in the immediate roof, a three-entry system development is simulated step by step by using the finite element method. In this study, the maximum horizontal stress is 3,000 psi, and the minimum horizontal stress is 1,500 psi. The simulated overburden depth is 800 ft. The roof consists of weak rocks. In the model, the entry width is 18 ft and the pillar is 80 ft wide and 100 ft long. The simulated mining height is 7 ft. The model is 700 ft wide and 700 ft long. Its height is 110 ft. The floor thickness is 50 ft. The angle between the maximum horizontal stress and the entry development direction is 60^0, because at this angle, the entry system is in the worset condition.

There are 8 steps in the simulating procedure, numbered step 1 ~ step 8. Each step is shown in Fig. 4-34. Since the maximum principal stress is distributed in the same way as the Von Mises stress, in this section only the Von-Mises stress distributions are analyzed.

Fig. 4-34 shows the Von-Mises stress distributions in all steps. In step 1, the stress is concentrated at the rib sides of entries, as previously discussed. When the crosscuts 3 and 4 are developed (step 2), the stress is concentrated at the corner between entry 1 and crosscut 3. It is also concentrated at the other corner between entry 3 and crosscut 4. But the former is larger than the latter, although the difference between them is small. Traditionally, it is thought that the latter should be larger than the former. Since the minimum horizontal stress exists and the rock is a solid material, not liquid, that traditional idea may not be correct (this will be discussed in the following section). In step 3, entry 1 is developed first. In this case, the stress at the right rib side is larger than that at the left side, and the stress at the corner between entry 1 and crosscut 3 decreases slightly. When entry 2 is developed first (step 4), the stress distribution is the same as that in step 3. The stress is concentrated at the two rib sides and the stress at the right side is larger than that at the left side. The stress at the corner between entry 2 and crosscut 4 decreases slightly. However, the stress at the other corner between entry 2 and crosscut 3 increases slightly. If entry 3 is developed first (step 5), the stress at the right side is larger than that at the other side, and the stress at the corner between entry 3 and crosscut 4 increases slightly. After entries 1 and 2 are developed, crosscut 5 is developed. When crosscut 5 is approaching entry 2, the stress at the roof between them is increasing, as shown in step 6 of Fig. 4-34. The stress at the left side of entry 2 is larger than that at the other side. This situation should be avoided. If crosscut 5 is developed first, the stress at the rib sides of entry 2 will be smaller. In step 7, crosscuts 5 and 6 are developed after the three entries are developed. In this case, in entry 1 the stress at the side near the crosscut 5 will increase as the crosscut 5 is approaching. In entry 3, the stress at the left side also increases as the crosscut 6 is approaching. In step 8, the crosscut 5 is developed before entry 2. The stress between the crosscut 5 and entry 2 is smaller than that in step 6. This development order is batter than that in steps 6 and 7.

Based on the stress distributions in the different steps, it is found that the Von-Mises stress is concentrated at the two rib sides of the entries and crosscuts. The stress at the one rib side is always larger than that at the other rib side. In some cases, the stress at the right side is larger than that at the left side, but in other cases, the stress at the left side is larger. However, the difference between them is not large. In addition, stress relief is not significant, although the stresses at some points are smaller.

In short, the development order of entries is not important from the stress point of view for this specific case. For example, there is no significant stress relief in the right side of entry 1 after entry 1 is developed. However, the sequence of developing crosscuts does have an influence on the stresses in entries, as shown in step 6 and step 7 of Fig. 4-34. The stress concentration may occur when crosscuts are approaching the entries (step 6 and step 7). Such situations should be avoided. But when a crosscut is developed first, the stress between the crosscut and an entry is smaller, as shown in step 8. This sequence of development is recommended.

It should be noted that the above results are for a specific case, namely, the pillar sizes are larger and the stress angle is 60^0. If a smaller chain pillar were used, the results may be different. In addition, when the angle is less than 45^0, the stress distributions in the immediate roof may vary.

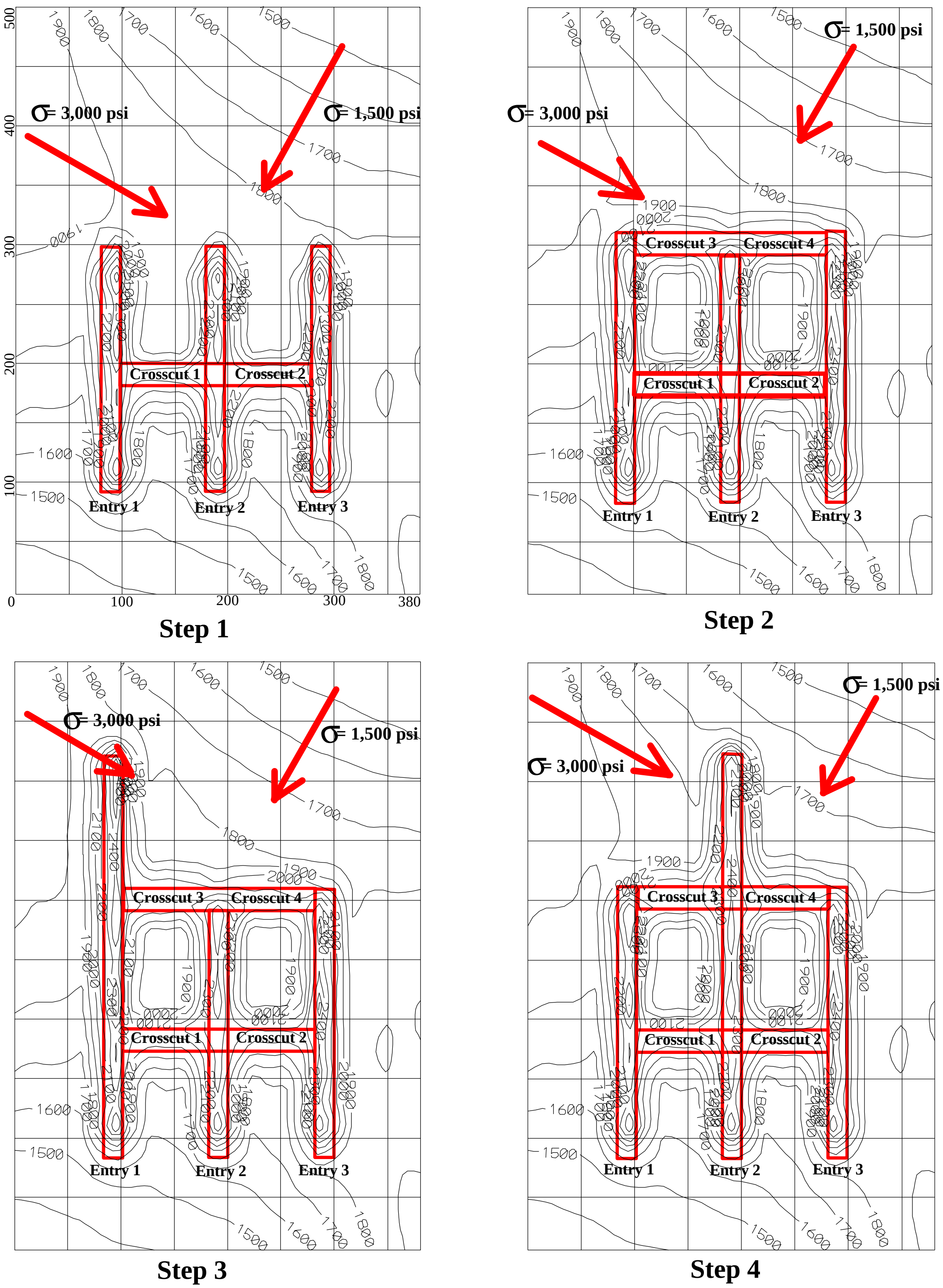


Fig. 4-34 Von-Mises Stress Contours in Sequence of Entry Development

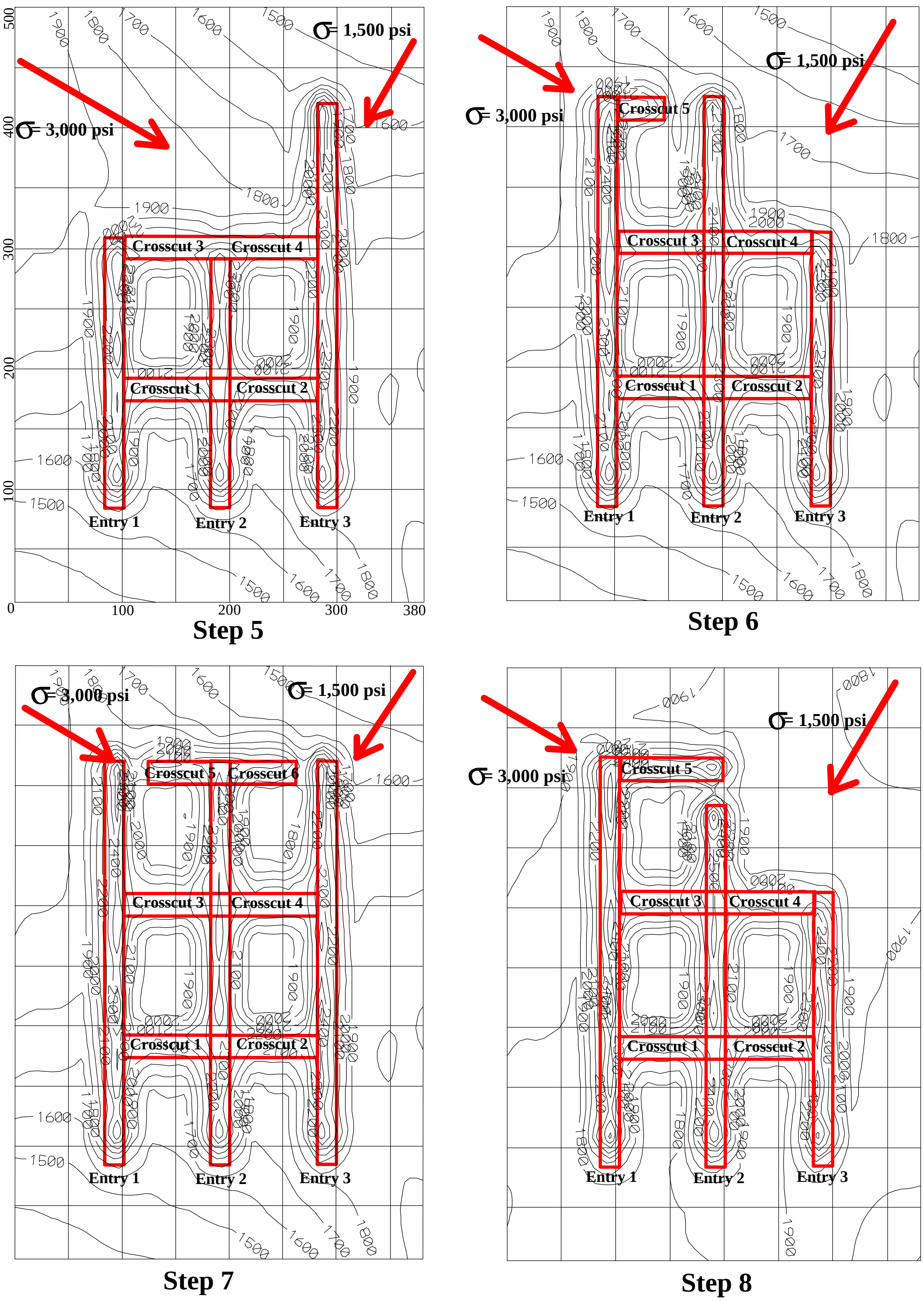


Fig. 4-34 Von-Mises Stress Contours in Sequence of Entry Development

4.8 Discussion of Results

Based on the above analysis of stress distributions, it is confirmed that the high horizontal stress does have a significant influence on longwall entries. Under high horizontal stress, the stress distribution is different from that without horizontal stress. Without horizontal stress, the stress in the immediate roof is distributed symmetrically. The stresses at the two rib sides of the entry are the same, and the tensile stress may occur at the center of the entry. Under high horizontal stress, generally the stress is not symmetrical. The stress at one rib side in the roof line level is larger than that at the other side, except in a few cases, such as when the angle is 0^0.

In a high horizontal stress field cutter roof is a common roof failure. But so far, little is known about the mechanism of cutter roof. Traditionally, it is thought that if the maximum horizontal stress is parallel to the entry, the roof will be in good condition because the entry face is shadowed by a horizontal stress relief zone, as shown in Fig. 4-35. If the horizontal stress is biased to the entry direction, the stress will be concentrated along one rib side and a cutter will be initiated along that side. When the horizontal stress is perpendicular to the entry, the entry will be in the worst condition because the horizontal stress is concentrated in front of the face. This interpretation is based on the flow mechanics. It can explain some situations. For example, the entry is in a good condition when the angle is 0^0, while it is in a bad condition when the angle is 90^0. However, the immediate roof of the entry is solid and continuous and the horizontal stress can pass through the roof. In addition, this interpretation does not consider the effects of the other principal horizontal stress which is also larger than the vertical stress.

Based on the previous stress analysis, it is found that cutter roof is a type of shear failure, because the Von-Mises stress is larger at the rib sides, as shown in Fig. 3-36. At the rib side, there are two stress concentration zones and the roof failure will initiate from one of these tow zones because the stresses are not the same in these two zones. The field measurements have confirmed that the cutter roof failure is a type of shearing failure (Figs. 2-18 & 2-19, p.20, Gale, 1991[13]).

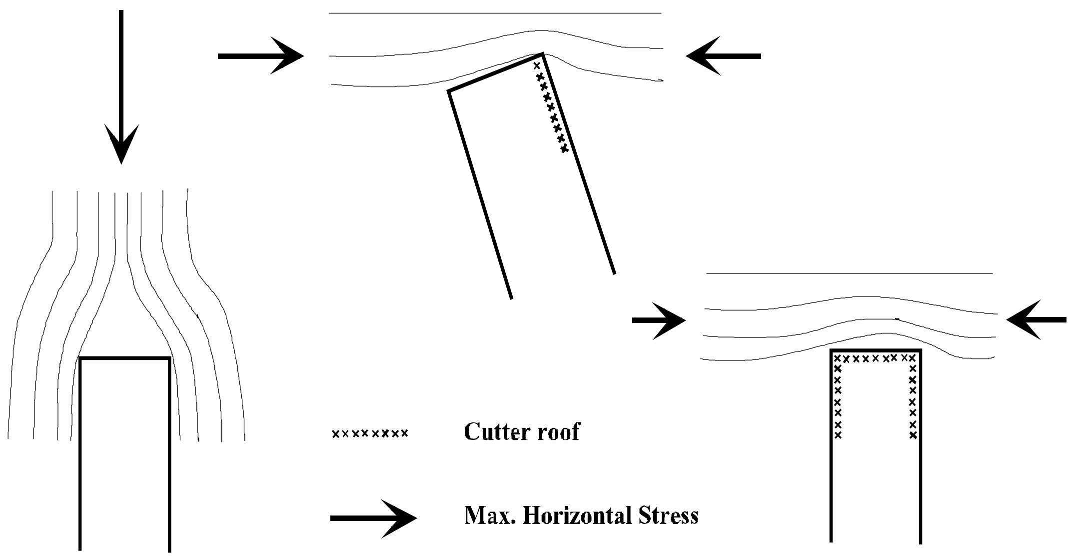


Fig. 4-35 Conceptual Explanation of Cutter Roof

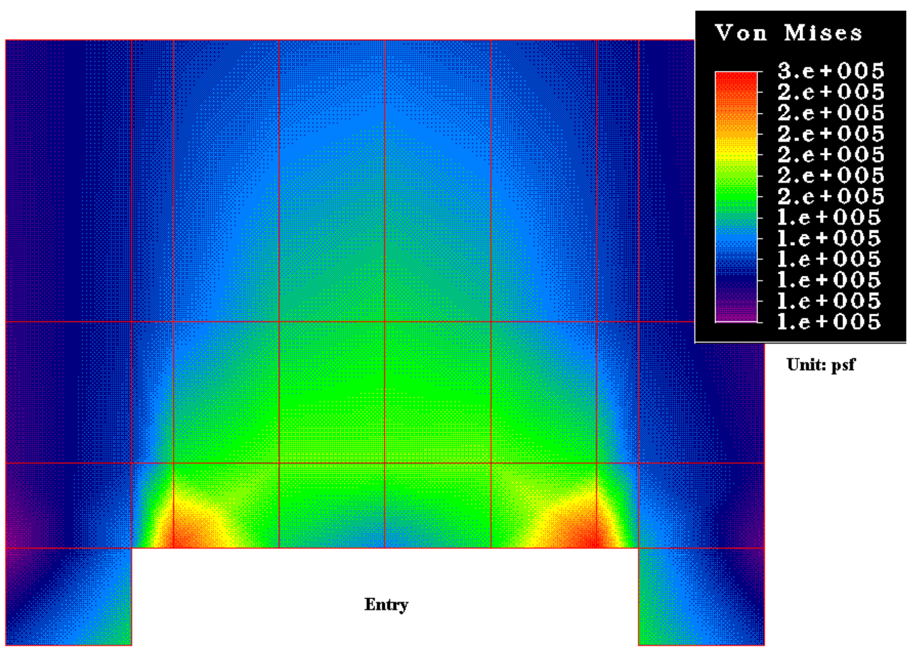


Fig. 4-36 Von-Mises Stress Distribution in Entry Roof

In a three-entry system, the Von-Mises stress and the maximum principal stress are greatly affected by the angle between the maximum horizontal stress and the entry development direction. When the maximum horizontal stress is from the solid side of entry 1, as shown in Fig. 4-1, the stresses are distributed in the following patterns:

(1) The Von-Mises stress and the maximum principal stress are concentrated at the rib sides of entries, and they increases with the angle from 0^0 to 60^0, and then decrease slightly from 60^0 to 90^0. Generally, they reach the maximum when the angle is about 60^0 to 75^0. The angle influence on the minimum principal stress is not significant.

(2) The stress at the one rib side is larger than that at the other side in each entry. In entry 1, the Von-Mises stress and the maximum principal stress at the solid rib side is larger than those at the other side. In entry 2, the stresses at the rib side near entry 1 are small than those at the other side. But the difference between them is small. In entry 3, the stresses at the rib side near entry 2 are smaller than those at the other side.

(3) The patterns of the Von-Mises stress distributions along the rib sides are also affected by the angle. When the stress angle is less than 45^0, the Von-Mises stress increases rapidly from the cross section A-A to the cross section B-B, then quickly decreases and keeps unchanged for a short distance. There is a peak value in the stress distribution along each rib side. When the angle is larger than 45^0, the stress rapidly increases from the cross section A-A to the cross section B-B, then slightly increases and keeps unchanged. In this situation, there is no peak in the stress distribution. At the center of the roof, the stress increases quickly from the cross section A-A to the cross section B-B, then rapidly reduces and keeps unchanged in a short distance, when the angle is from 0^0 to 90^0.

(4) The minimum principal stress is slightly affected by the angle. The stress slightly increases with the angle. In addition, the tensile stress in the roof subject to a high the horizontal stress is much less than that without horizontal stress.

(5) The stress ratio of the maximum to the minimum horizontal stresses is a factor affecting the stress in the immediate roof. But its effects depend on the angle. When the angle is equal to or less than 45^0, the Von-Mises decreases with the ratio from 1.0 to 2.0, and then reduces very slightly from 2.0 to 3.0. When the angle is larger than 45^0, the ratio influence on the Von-Mises stress can be ignored.

(6) When the maximum horizontal stress is larger than 3,000 psi, the overburden depth has a small effect on the Von-Mises and the maximum principal stresses in the immediate roof when the overburden depth ranges from 500 ft to 1,300 ft. However, the minimum principal stress reduces with the overburden depth, namely the tensile stress increases with the overburden depth.

(7) When the maximum horizontal stress increase from 3,000 psi to 4,500 psi (the ratio is 2.0), the stress at the roof line level increases. But its pattern keeps the same.

(8) The roof property also affects the stress in the immediate roof. Generally, the harder the immediate roof, the larger the stress in the roof. But the pattern of stress distribution does not change with the roof properties. In this study, two types of roof, weak roof and medium roof, are involved. The patterns of stress distributions are the same in these two types of roof.

(9) The sequence of developing entries has a little effect on the stress in the immediate roof for the specific case studied. As discussed in the previous section, the order of developing three entries does not influence the Von-Mises stress distributions in the roof. But when a crosscut approaches an entry, a larger stress concentration may occur, as shown in Fig. 4-34 steps 6 and 7.

Traditionally, it is recognized that the stress angle between the entry direction and the maximum horizontal stress is the most important factor affecting the roof stability. The field measurements have also confirmed that an entry may be in the worst condition when the stress angle is 90^0, as shown in Figs. 18 and 2-19 (p.20). But the location of roof failure moves toward the entry center when the angle is about 80^0~90^0, according to those figures. It implied than the stress at the rib sides should decreases slightly when the angle more than 75^0.

This paper focuses on the stress distributions of three types of stresses in longwall entries, namely the Von-Mises stress, the maximum and the minimum principal stresses. The typical roof stress distributions in the three entry system are shown in Figs. 4-37 ~ 4-39. These figures show the Von-Mises stress, the maximum principal stress, the maximum shearing stress, and the stress ratios with the different stress angles. In these figures, the maximum shearing stress (τ_{max}) and the stress ratio (R_s) are defined by the following equations:

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2}$$

$$R_s = \frac{\sigma}{\sigma_{\alpha=0}}$$

where σ_1, σ_3 – the maximum and the minimum principal stresses;

σ – stress for different stress angle; and

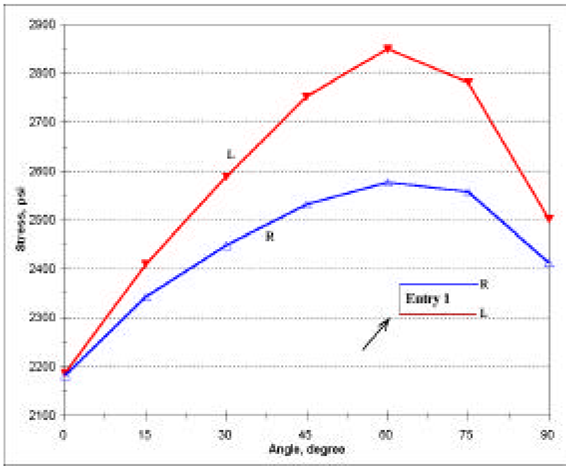
$\sigma_{\alpha=0}$ – stress when the stress angle is equal to 0^0.

These figures indicate that the conclusions about the influence of the stress angle on the roof stability are slightly different when the different rock failure criteria are used. For example, in entry 2, the entry is in the worst condition from the Von-Mises stress point of view when the angle is about 60^0~75^0. However, if the maximum shearing stress criterion is used, the entry is in the worst condition when the angle is equal to 90^0. Since this study does not refer to the rock failure criteria, the differences between them are not discussed here.

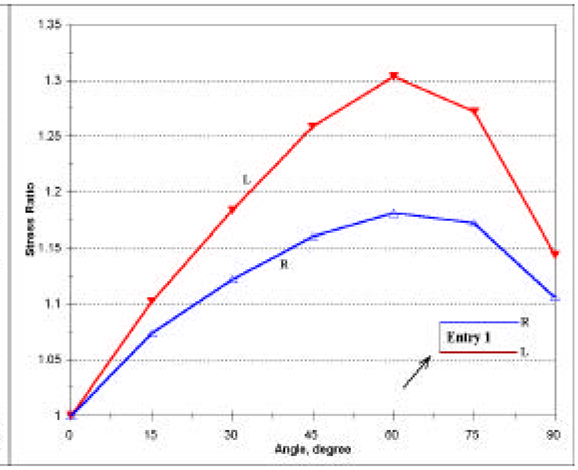
Fig. 4-40 shows the Von-Mises stress in a longwall entry roof (Su and Hasenfus, 1995). When the angle is less than 90^0, its distribution is similar to the Von-Mises stress distributions discussed previously. But, the stress distribution is not reasonable when the angle is larger than 90^0. For example, when the angle increases from 90^0 to 112.5^0, the stress decreases so quickly. Since the information about the model sizes and the location of the measurement point in Su and Hasenfus' study is not available, the detailed discussion can not be performed.

Generally speaking, the longwall entries are in the worst condition when the angle is about 60^0~90^0, no matter what type of the failure criteria is used. When only one entry is developed, the Von-Mises stress increases with the stress angle from 0^0~90^0. In a three-entry system, the stress increases with the angle from 0^0~60^0(or 75^0), and then decreases slightly from 60^0(or 75^0)~90^0. In addition, when the stress angle changes from 0^0 to 90^0, the roof stress increases about 30~40%, compared with the stress when the angle is equal to 0^0. Based on the Von-Mises stress distributions, the locations of possible cutter roof failures in a three-entry system are shown in Fig. 4-41.

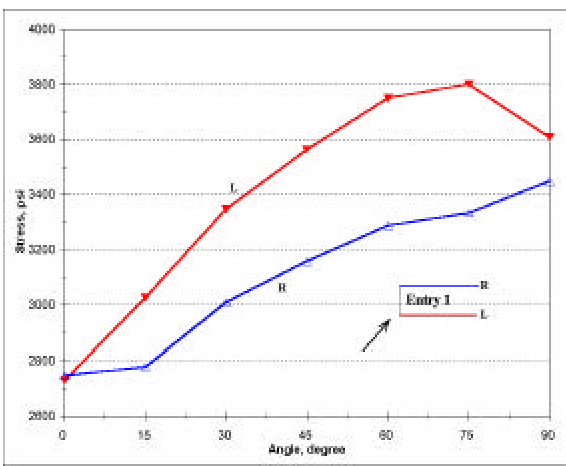
In coal seam, the stress distributions are similar to those in the immediate roof. Figs. 4-42 and 4-43 show the Von-Mises and the maximum principal stress around entry 2. Since this study is concerned with the stress distributions in the roof, the stress in the coal seam is not discussed.



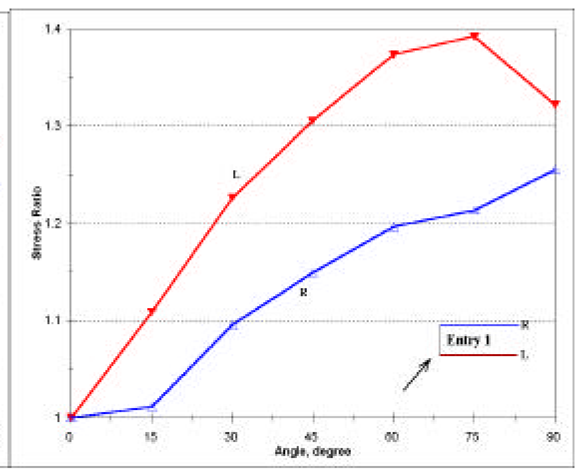
(a) Von-Mises Stress



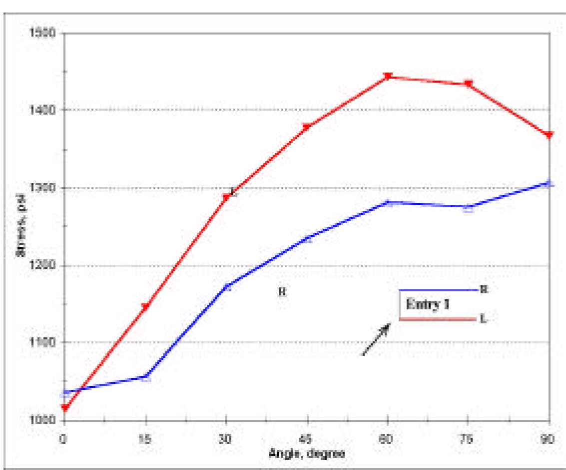
(b) Von-Mises Stress Ratio



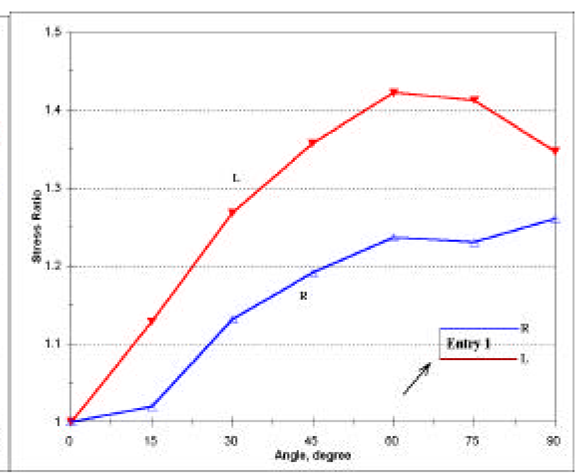
(c) Max. Principal Stress



(d) Max. Prin. Stress Ratio

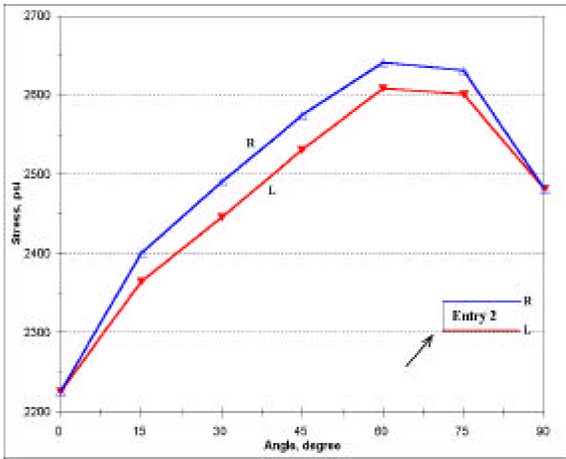


(e) Max. Shearing Stress

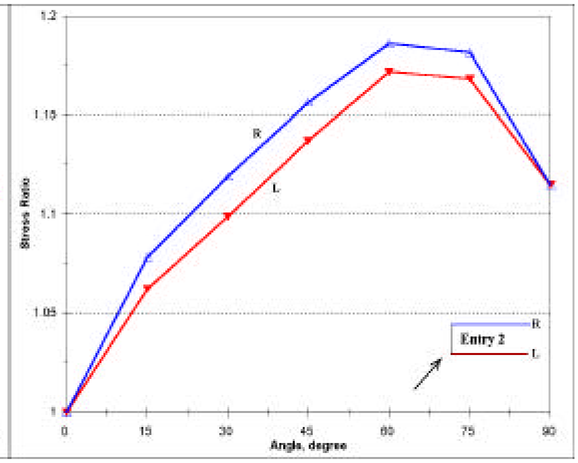


(f) Max. Shearing Stress Ratio

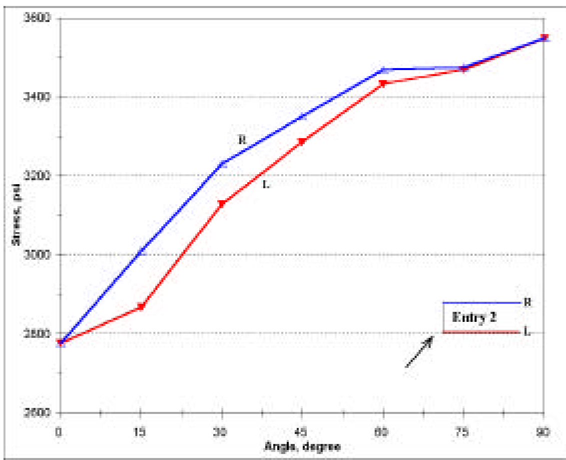
Fig. 4-37 Typical Roof Stress Distributions for Different Stress Angles in Entry 1



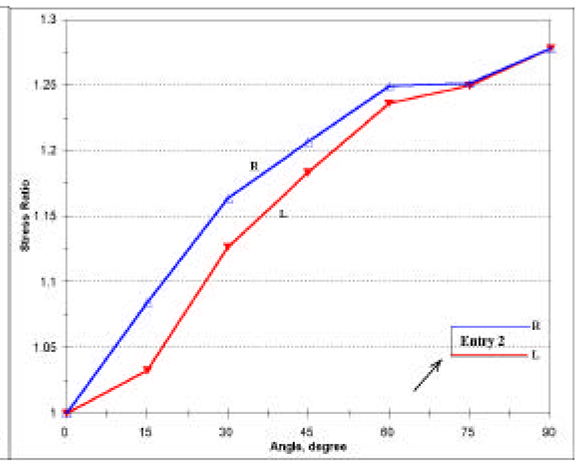
(a) Von-Mises Stress



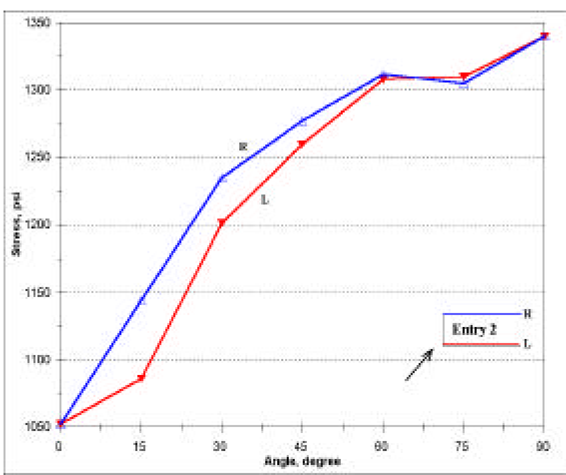
(b) Von-Mises Stress Ratio



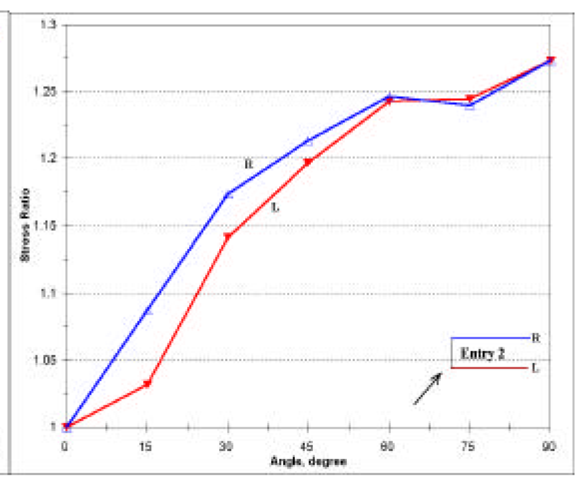
(c) Max. Principal Stress



(d) Max. Prin. Stress Ratio

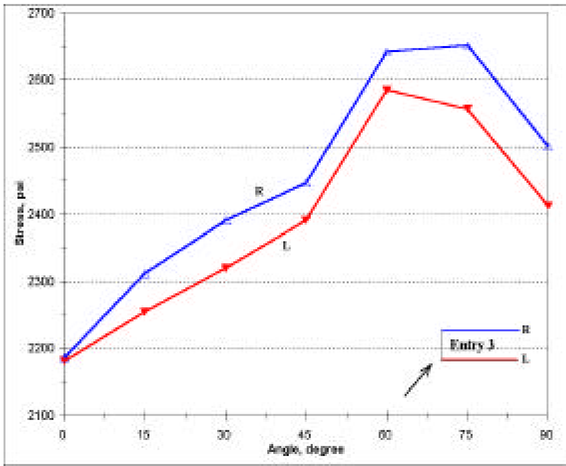


(e) Max. Shearing Stress

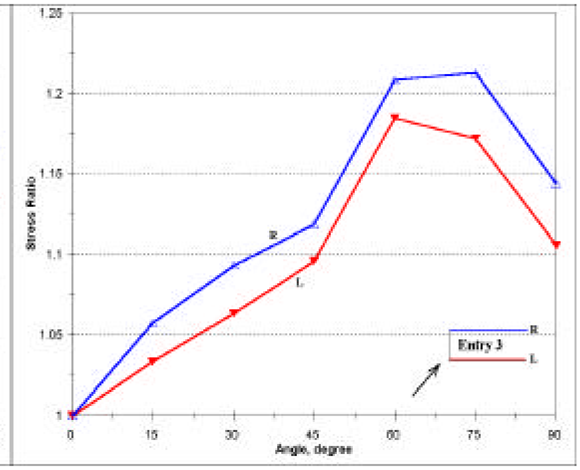


(f) Max. Shearing Stress Ratio

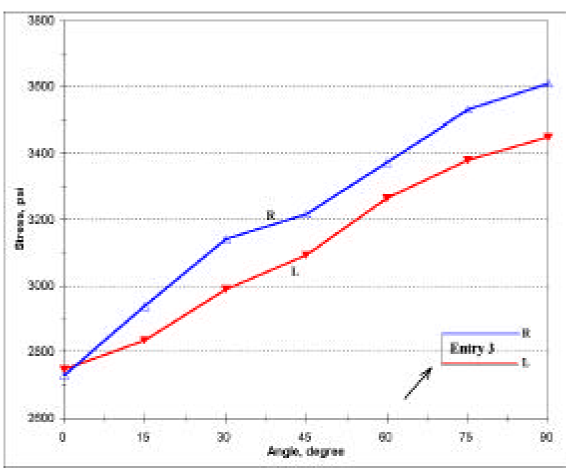
Fig. 4-38 Typical Roof Stress Distributions for Different Stress Angles in Entry 2



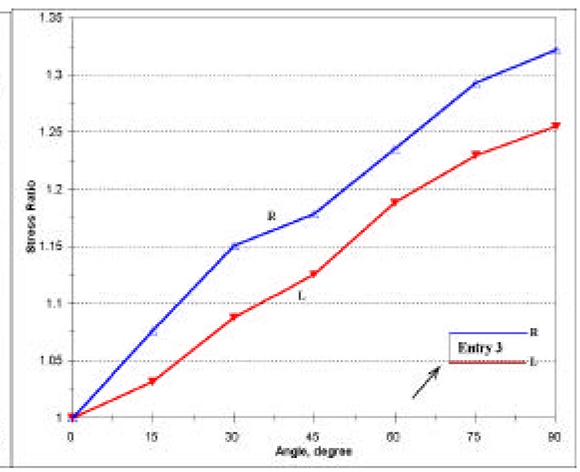
(a) Von-Mises Stress



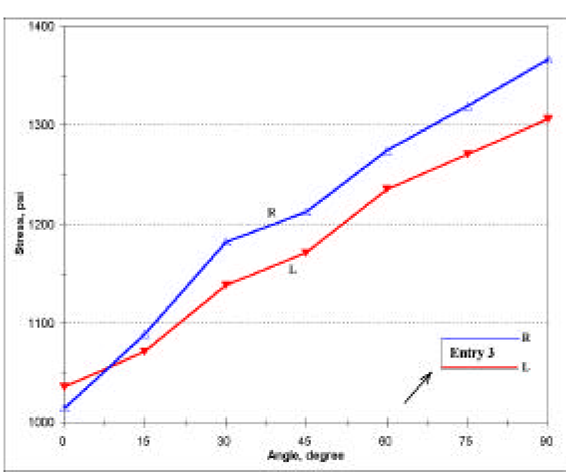
(b) Von-Mises Stress Ratio



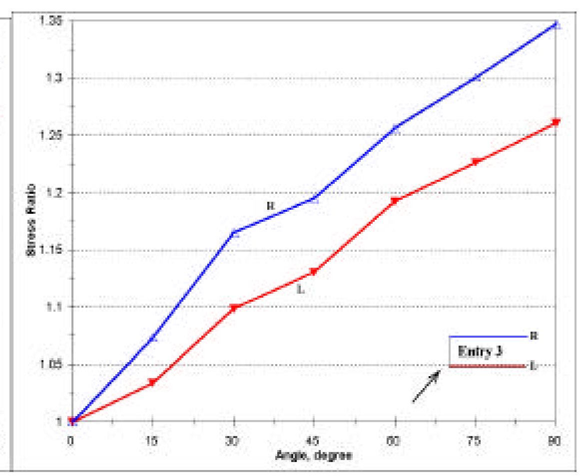
(c) Max. Principal Stress



(d) Max. Prin. Stress Ratio

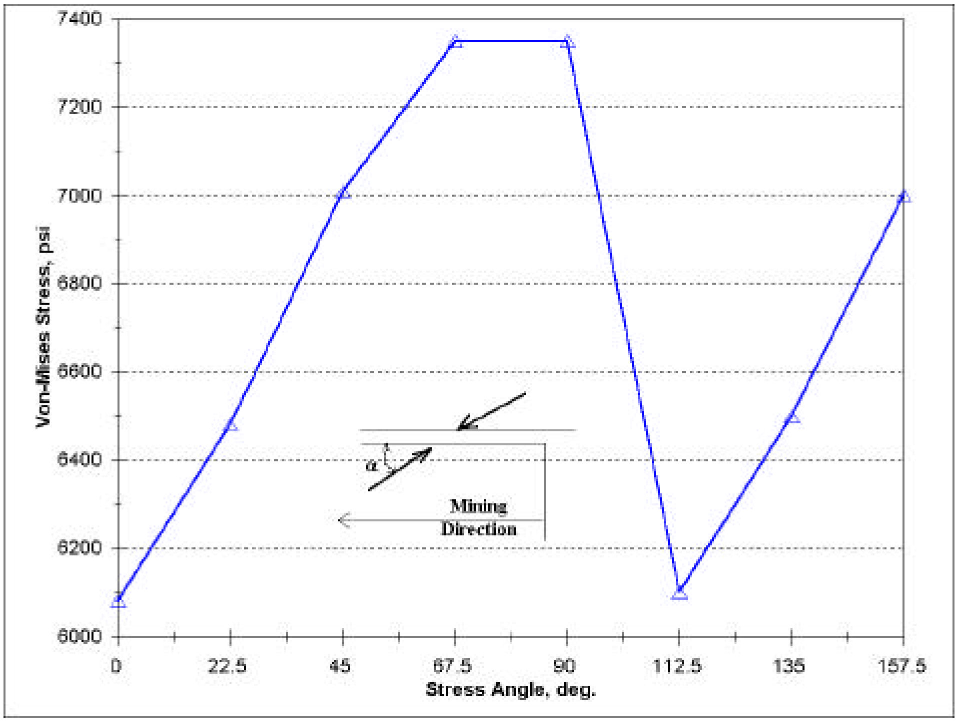


(e) Max. Shearing Stress

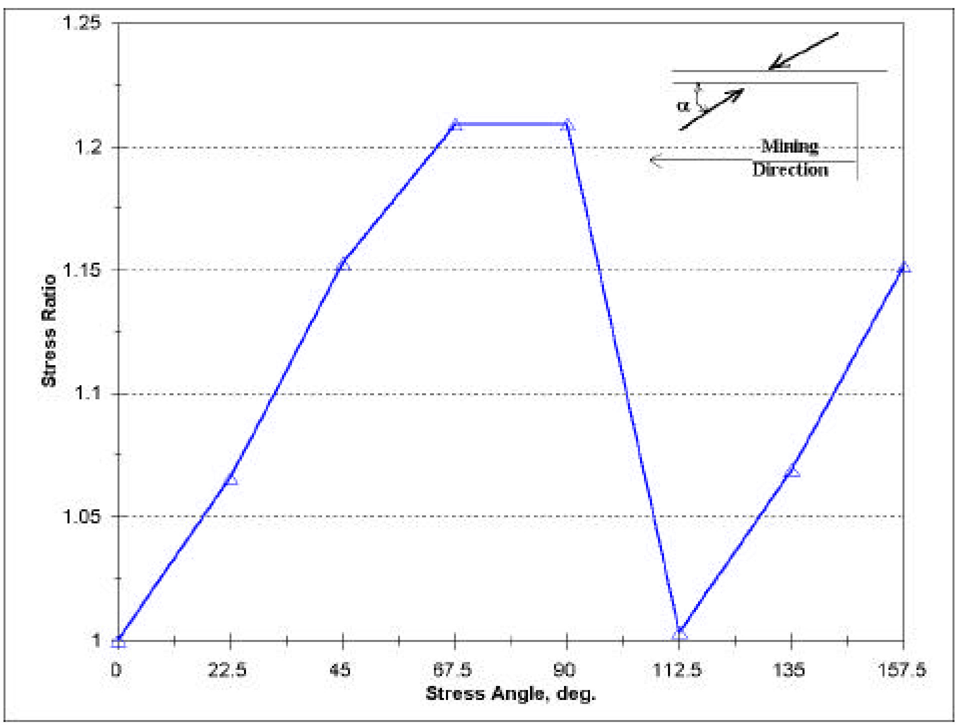


(f) Max. Shearing Stress Ratio

Fig. 4-39 Typical Roof Stress Distributions for Different Stress Angles in Entry 2



(a) Von-Mises Stress



(b) Von-Mises Stress Ratio

Fig. 4-40 Von-Mises Stress after Entry Development (Su and Hasenfus, 1995[39])

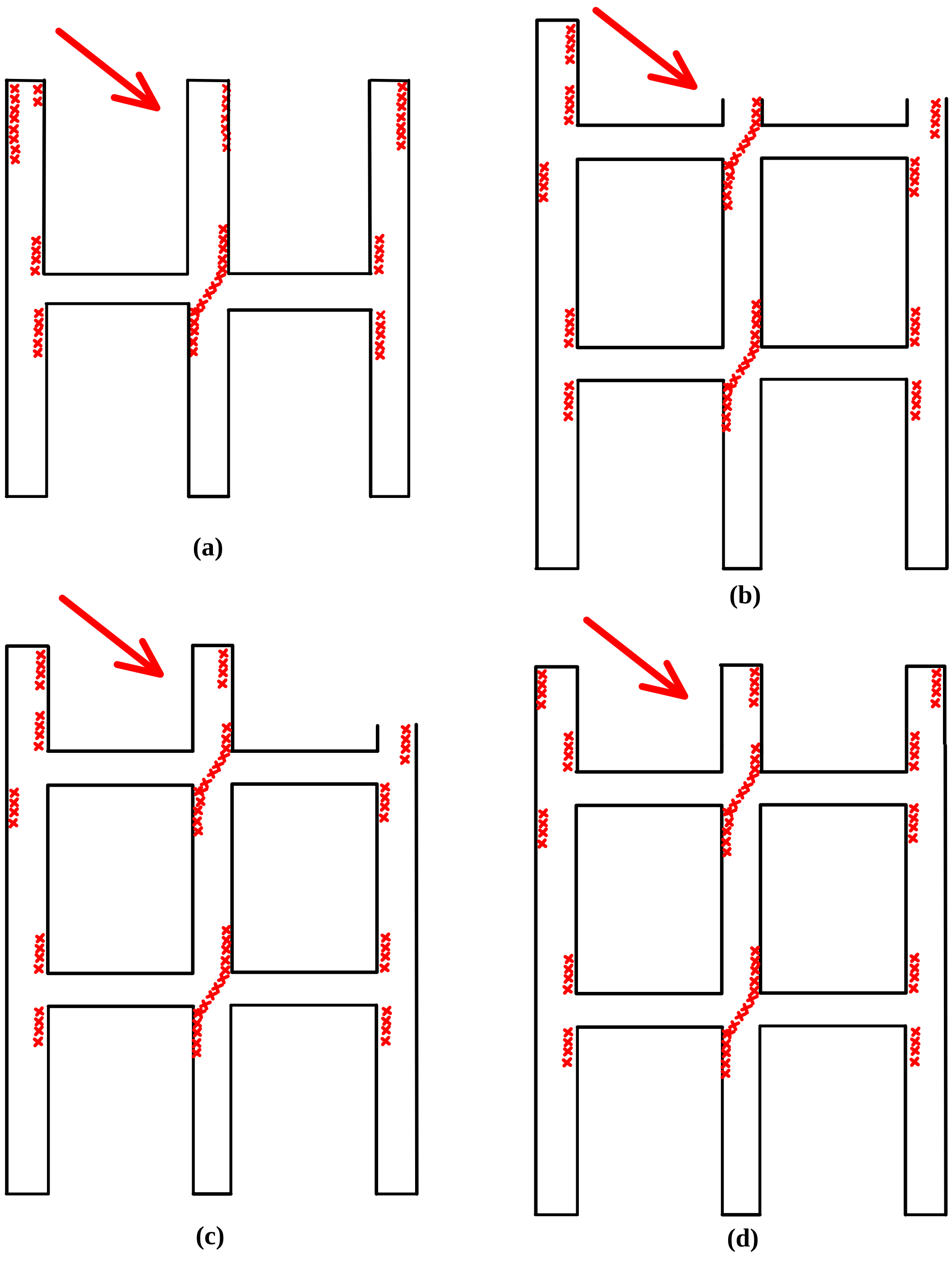


Fig. 4-41 The Possible Locations of Cutter Roof

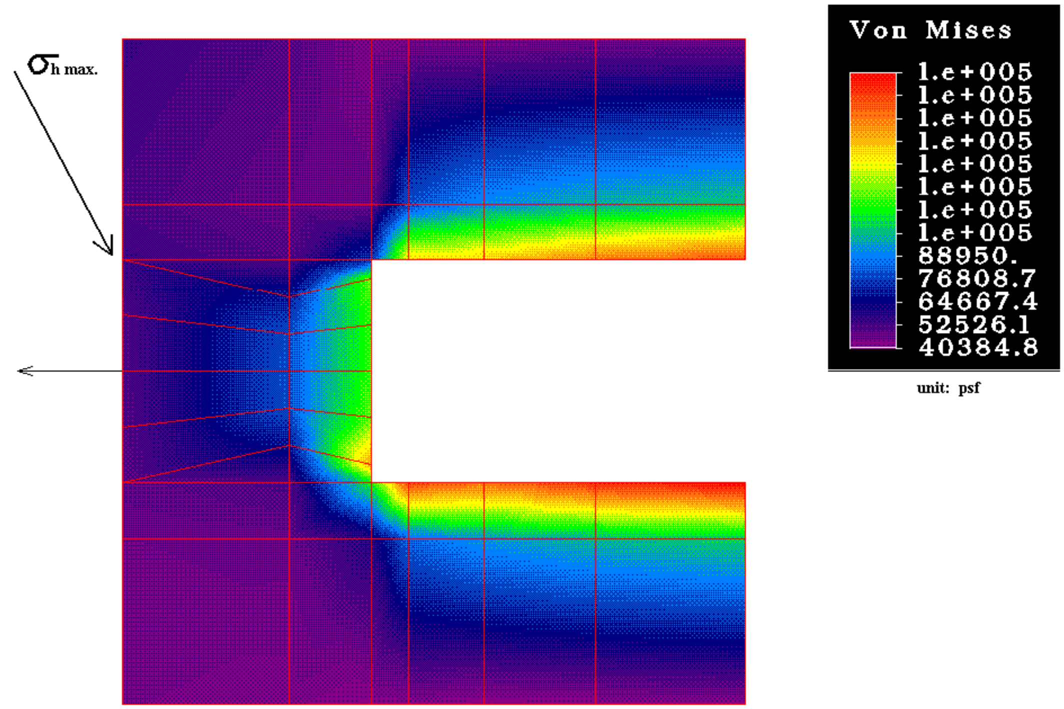


Fig. 4-42 Von-Mises Stress in Coal Seam around Entry 2

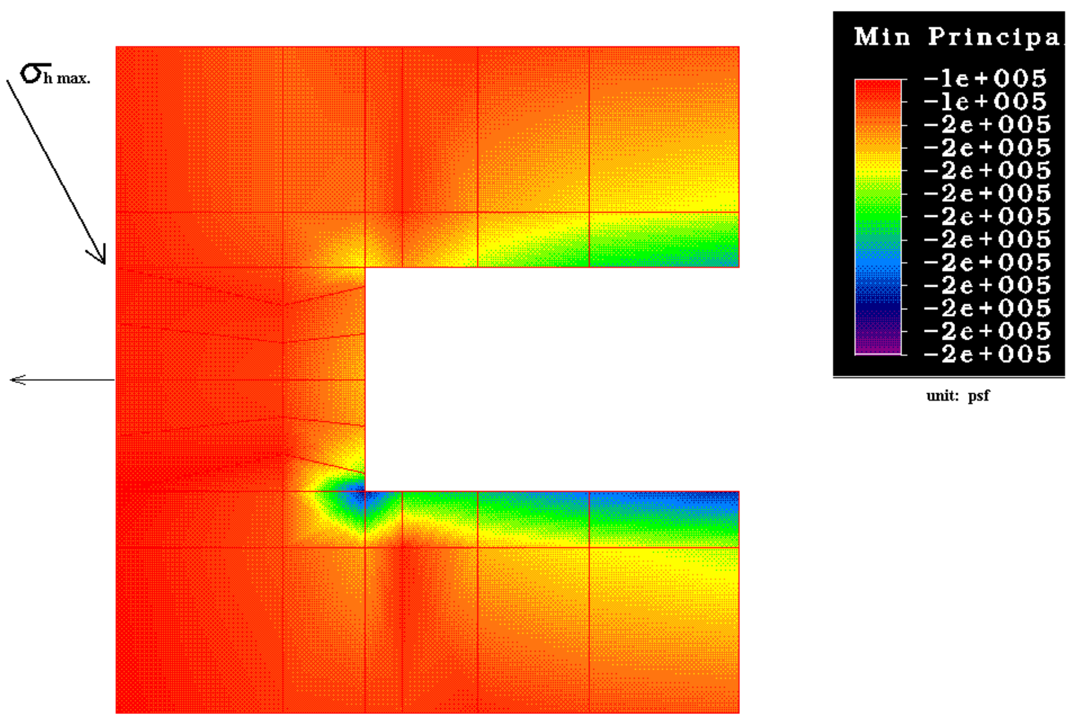


Fig. 4-43 Max. Principal Stress in Coal Seam around Entry 2