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Measurement of the Structure of Turbulence in Symmetric Wall Subchannels with P/D = 1.148 and W/D = 1.074

Abstract

Measurements of the mean velocity, the wall shear stresses, and the turbulent Reynolds stresses were performed in two symmetrical wall subchannels of a rod bundle. The rod bundle of four parallel rods was arranged symmetrically in a rectangular channel with a pitch-to-diameter ratio of P/D = 1.148 and a wall-to-diameter ratio of W/D = 1.074. The Reynolds number of this investigation was $Re = 7.07 \times 10^4$.

The experimental results show that the structure of turbulence in this rod bundle differs greatly from the structure in circular tubes. Especially in the narrow gaps between the rods and the channel walls there are increased levels of turbulent intensities in the axial and azimuthal directions and, hence, of the kinetic energy of turbulence. In contrast to a previous investigation in this geometry, however arranged asymmetrically in the rectangular channel, the momentum transport between the subchannels across the gap between the rods is negligible.

The comparisons between experimental wall shear stress distributions and those computed by the VELASCO code shows strong deviations, especially in the gaps between the rods and channel walls.

Messungen der Turbulenzstruktur in symmetrischen Wandkanälen mit P/D = 1.148 und W/D = 1.074

Zusammenfassung

In zwei symmetrischen Wandkanälen eines Stabbündels wurden Geschwindigkeits-, Wandschubspannungsverteilungen und Verteilungen der Reynoldschen Spannungen gemessen. Das Stabbündel aus vier parallelen Stäben war symmetrisch in einem Rechteckkanal mit einem Stababstandsverhältnis von P/D = 1.148 und einem Wandabstandsverhältnis von W/D = 1.074 angeordnet. Die Reynoldszahl der Untersuchung betrug Re = 7.07×10^4.

Die Meßergebnisse zeigen, daß die Struktur der Turbulenz in Stabbündeln stark von der Struktur in Kreisrohren abweicht. Besonders im engen Spalt zwischen Stab- und Kanalwänden gibt es erhöhte Turbulenzintensitäten in axialer und azimutaler Richtung und damit auch eine erhöhte kinetische Energie der Turbulenz. Im Gegensatz zur früheren Untersuchung an dieser Geometrie, jedoch in asymmetrischer Anordnung, ist der Impulstransport durch den Spalt zwischen den Stäben vernachlässigbar.

Der Vergleich der gemessenen mit den vom Rechenprogramm VELASCO berechneten Wandschubspannungsverteilungen zeigt starke Abweichungen, insbesondere in den Spalten zwischen Stab- und Kanalwänden.

Measurement of the Structure of Turbulence in Symmetric Wall Subchannels with P/D = 1.148 and W/D = 1.074

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1. Introduction

The prediction of the detailed temperature distribution on the fuel elements in rod bundles is of particular significance in the design, safe and reliable operation and safety analysis of nuclear reactors. So far, the methods of thermal-hydraulic analysis of nuclear reactors, which are based on the solution of the conservation equations of mass, momentum and energy, can be classified into three categories /1/: subchannel analysis, porous body model analysis and distributed parameter analysis. Both subchannel analysis and porous body model analysis, are lumped parameter approaches: average mass flow rates and temperatures within the individual control volumes are computed and the fine structure of velocity and temperature within the control volumes is ignored. Therefore, most of the calculated cladding temperature distributions are too inaccurate for subsequent structural analysis /2/. The distributed parameter analysis method with turbulence models under active development /3,4,5/ could be used to calculate detailed velocity and temperature distributions. However, the calculated results and their accuracy depend on the correctness of the turbulence modelling. Empirical information on turbulent momentum and energy transport properties between subchannels is needed for the development of distributed parameter codes. Detailed experimental data of velocity, turbulence and temperature distributions is necessary for validation and improvement of turbulence modelling. For this reason, a series of experimental investigations on flow through subchannels of rod bundles were performed at KfK during the past ten years. An overview is presented in /6/ on the investigations performed, the important observations, and the main impact on turbulence modelling for distributed parameter analysis. A vast amount of valuable data and a profound knowledge on turbulent flow through rod bundles have been achieved. The measurement of the structure of turbulence in a symmetric wall subchannel with P/D = 1.148 and W/D = 1.074 described in this report is one of the series of the experimental investigations mentioned above.

In a previous report /7/, the experimental results were presented on flow through a wall subchannel with the same pitch-to-diameter ratio of P/D = 1.148 and wall-to-diameter ratio W/D = 1.074 as in this investigation recently performed. But in that case, the investigated subchannel was located in a geometrically asymmetrical arrangement of the subchannels of the rod bundle. That means, the investigated wall subchannel was adjacent to a wide subchannel. It has been found that a strong momentum transport from the adjacent wide subchannel obviously affects the flow characteristics in the narrow subchannel. In this investigation, the measured data were evaluated with the same method as in /7/. Therefore, the comparison between the results of these two investigations could clearly demonstrate the influence of geometric asymmetry on the turbulent structure in a wall subchannel of rod bundles. In this report, the results of an experimental investigation are presented on the flow through two symmetric wall subchannels of a rod bundle divided into four symmetric quadrants (Q1 to Q4) with a pitch-to-diameter ratio P/D = 1.148 and wall-to-diameter ratio of W/D = 1.074. All measurements were performed by a fully automated system controlled by a computer /9/. The full Reynolds stress tensor was measured. Hooper's method /10/ was applied for evaluation of the hot wire data /11/. The results are compared with the previous data /7/. Some new observations near the gap region between the rods are achieved.

2. Experimental Setup

The experiment was performed on the computer controlled experimental rig /9/ of KfK-INR with air as the working fluid. Fig. 1 shows the schematic of the test rig. Air was taken in through a silencer and entered the test section through a honeycomb grid located in the lower plenum.

The test section consists of a rectangular channel of 159.8x700 mm^2 cross section and a rod bundle of four parallel rods (139.0 mm O.D.) enclosed in the channel. The rods were fixed inside the channel with small pins of 2 mm O.D. as spacers at four levels along the longitudinal axis. The full length of the test section of L = 7800 mm was made up by four parts, each of which had a length equal to 1950 mm. The rods were made of aluminium tubes, the outer surfaces of which were machined. The mean roughness depths of the surface amounted to only 0.6 µm. The rod bundle is symmetrically arranged with a P/D = 1.148 and W/D = 1.074 as shown in Fig. 2. The hydraulic diameter of the investigated wall subchannel was $D_h = 5.47 \times 10^{-2}$ m.

The measurements were perfomred at a level about 30 mm upstream of the open outlet, so the ratio of length to hydraulic diameter at the measuring plane was $L/D_h = 142.0$.

Table 1 shows the geometry parameters in the four quadrants in detail (the positions of the quadrants are indicated in Fig. 2). It is clear from Table 1 that there are only very small deviations from symmetry between the four quadrants due to assembling tolerances. Each quadrant was divided into two parts by the imaginary line of maximum normal distance from the walls. The measurements were carried out in 8 parts of the four quadrants. The data was recorded in kartesian coordinates in the part close to channel walls and in cylindrical coordinates in the part close to the rod wall, with some overlapping.

In order to achieve the necessary accuracy of the gradients of the measured data, the flow cross section was covered by a fine network of mesh points. Measurements were taken on traverses every 5° along the rod walls and every 5 mm along the channel walls at 7 to 20 points on each traverse normal to the walls depending on the width of the flow cross section. The total number of measuring points was about 400 in each quadrant.

The following physical parameters were measured:

1. the time-mean axial velocity measured with a Pitot tube of 0.6 mm O.D.,

2. the wall shear stresses measured with a Preston tube using the correction of Patel /12/, and

3. the turbulence intensities and the full Reynolds stress tensor measured with a single normal hot wire DISA Model 55P12 and a single slanting wire DISA

Model 55 P11 and a constant-temperature anemometer bridge DISA Model 55 M01.

The nonlinear output signal of the anemometer was used for the calculation of the Reynolds stresses. The hot-wire probes were statically calibrated before every time of use.

During the experiment, the Reynolds number was kept constant at a fixed point in the channel by setting a reference pressure drop under reference conditions and automatically adjusting the speed of the blower. In this investigation, the average Reynolds number based on the average velocity in the two wall subchannels was:

$$Re = 7.067 \times 10^4$$

The reference condition was:

$$T_{REF} = 25°C$$

$$P_{REF} = 0.1 \text{ MPa}$$

The reference velocity at the fixed point was:

$$U_{REF} = 27.75 \text{ ms}^{-1}$$

3. Experimental Results and Discussion

All experimental data are corrected to the reference conditions. The corrections were discussed in detail in /10,11/. Hooper's method /10/ was used for evaluation of the hot wire data. All tabulated results are available from the authors.

The axial velocities and the turbulence results are shown in complete contour plots of the four quadrants and in linear plots in order to describe more distinctly the flow characteristics in the field.

In this report, the experimental results are discussed in the same sequences of sections as in /7/ for convenience of comparison.

3.1 Time Mean Axial Velocity

The time-mean axial velocity distribution is shown as a contour-plot (Fig.5) and in linear plots (Figs. 3 and 4). The time-mean axial velocity measured by a Pitot tube is presented in the contour-plots as a relative velocity related to the reference velocity U_{REF} at a fixed point under reference conditions. In the linear-plots, the velocities shown are related to the average velocity in the quadrant. The velocity distributions on each traverse are shown as a function of the relative distance from the wall Y/L (L is the distance from the wall to the line of maximum velocity). Figures 3-1 to 3-4 show the time-mean velocity distributions along each traverse from the wall in the area near the rod walls in r/Φ coordinates. (Notice, in this report a number with two digits is used to describe the sequence of the figures. The first digit shows the sequence of the figures and the second digit shows the quadrant number).

Figures 4-1 to 4-4 show the time mean velocity distributions in the area near to channel walls in x/y coordinates. The following characteristics of the time-mean velocity distributions are noticeable:

1. The velocity distributions in the four quadrants show a good symmetry
2. The lowest velocities are found in the gaps between the rods and channel walls ($x = 0$ mm, $\Phi = 90°$)
3. There exists a maximum velocity area near the center of the channel section that is at $x = 80$ mm, $\Phi = 35°$. The maximum velocities are not found at the intersection point of the lines of maximum nomal distance from the walls but with a little deviation towards the channel walls.
4. There is a saddle point of the velocity distribution in the gap between the rods with a relatively low value of the time mean velocity. But it is still higher than that at the gap between the rods and channel walls (0.79 against 0.60).
5. The smooth velocity contour lines are almost parallel to the walls with quite perfect symmetry.
6. The contour lines are perpendicular to the boundary lines of the subchannel in the gap regions that means there is no momentum transport by viscous

shear stress and a mean velocity gradient between two adjacient subchannels.

7. It can be judged that there is no significant secondary flow influence from the trend of the contour lines.

The average velocities in each part (r/Φ or x/y) of the four quadrants and in each quadrant were obtained by integration of the velocity distribution. Table 2 shows the average velocities in each part and their deviations from the average. The maximum discrepancy between the four symmetric parts (r/Φ) is $\Delta_{max,\, r/\Phi} = 1.49\%$, between the four symmetric parts (x/y) it is $\Delta_{max,x/y} = 1.60\%$, and between the four symmetric quadrants it is $\Delta_{max,Q} = 1.53\%$. The discrepancies show further quantitatively the almost perfect symmetry of the flow field in the four quadrants.

A comparison of the local velocities at every four symmetric points on all four symmetric traverses in the four quadrants shows that the maximum discrepancy is 5.40% for the r/Φ-parts and 3.83% for the x/y-parts (see table 3). The total average velocity in the two wall subchannels investigated is 20.36 ms^{-1}.

The nondimensional velocity distribution U^+ scaled by the local friction velocity $U^*(U^* = \sqrt{\tau_w/\rho},\ U^+ = U/U^*)$ is shown in Figs. 6-1 to 6-4 for the r/Φ-parts and in Figs. 7-1 to 7-4 for the x/y-parts of the four quadrants as a function of the nondimensional distance from the wall Y^+ ($Y^+ = YU/\nu$, Y is the normal distance from the wall along the traverses). The Nikuradse law of the wall in circular tubes /13/

$$U^+ = 2.5 \ln Y^+ + 5.5 \qquad (1)$$

is also shown in the figures.

It should be noted that the nondimensional velocity distributions in the wall subchannel of the rod bundle closely agree with the law in circular tubes, except for the small deviation in the area far from the walls.

3.2 Wall Shear Stress

The wall shear stress distributions on the tube and channel walls were measured with a Preston tube. The experimental results of the wall shear stress scaled by the average in the relevant quadrant are listed in Table 4 to Table 7 for quadrant

1 to quadrant 4, respectively. Figure 8 shows the wall shear stress distribution along the channel walls of the whole wall subchannel and Fig. 9 shows the wall shear stress distribution along the rod walls.

Following characteristics are notable:

1. The wall shear stress gradient in circumferential direction both at the rod gap and at the gaps between the rod and channel wall is close to zero, except for a slight shift of the zero gradient point at the gap between rod and channel wall on the channel wall for quadrant 1. This once more demonstrates that there is no significant momentum transport due to the average velocity distribution through the boundaries between symmetric subchannels or quadrants. This results agree with the results of the velocity distribution.

2. The wall shear stresses reach maxima at the positions on the wall with widest traverse ($\phi = 35°$; $x = 0$ mm on Fig. 8 and Fig. 9, respectively), where the average velocity displays also its maximum values (see Fig. 5).

3. The distributions of the wall shear stress show a relatively good symmetry except for a lower peak value on the rod wall in the quadrants 2 and 3. The maximum discrepancy of the average wall shear stresses in the four quadrants accounted to 3.78%. The maximum discrepancy between the four symmetric parts r/ϕ is $\Delta_{max,\ r/\phi} = 3.45\%$, and the maximum discrepancy between the four symmetric parts x/y is $\Delta_{max,\ x/y} = 1.11\%$.

The average wall shear stress in the two wall subchannel is:

$$\tau_{w,av} = 1.12 \text{ Pa.}$$

3.3 Friction Factors

The average friction factors were calculated from the measured wall shear stresses in the four quadrants:

$$\lambda_\tau = 8\tau_{w,av}/(\rho U^2_{av}) \qquad (2)$$

The friction factors also were calculated from the measured pressure drop along the channel axis:

$$\lambda_{\Delta p} = \frac{\Delta p/\Delta L}{\rho U_{av}^{2}/2D_h} \qquad (3)$$

Here, the measured pressure drop across the length $\Delta L = 1.262$ m under the measurement conditions is $\Delta p_m = 112.8$ Pa. This measured pressure drop was corrected to the reference conditions by:

$$\Delta_{pR} = \Delta_{pm} \frac{\rho_m}{\rho_{REF}} \left(\frac{\mu_{REF}}{\mu_m}\right)^2 \qquad (4)$$

$$\Delta_{pR} = 111.2 \text{ Pa}$$

Based on the corrected pressure drop, the friction factors $\lambda_{\Delta p}$ were calculated and the results are listed in Table 8.

The friction factors both based on the pressure drop measurement and on the wall shear stress measurement agree very well. This is due to the good symmetry of the flow field. The results of the friction factors indicate once more that there is no significant influence of a viscous momentum transport through the boundaries between the quadrants.

In order to compare the experimental results with a theoretical value, the friction factor was also calculated by Rehme's method /14/ and /15/. Under laminar flow conditions:

$$\lambda \cdot Re = K \qquad (5)$$

When P/D = 1.148 and W/D = 1.074

$$K = 61.1$$

while under turbulent conditions

$$A = 1.01$$

$$G^* = 5.67.$$

The friction factor λ in the wall subchannel of this rod bundle is described by the equation:

$$\sqrt{\frac{\lambda}{8}} = A \left[2.5 \ln\left(Re\sqrt{\frac{\lambda}{8}}\right) + 5.5\right] - G^* \qquad (6)$$

For Re = 7.067 x 10^4, the friction factor λ_{th} was computed to

$$\lambda_{th} = 0.01912$$

Compared with the experimental result of λ_t , the deviation between the theoretical value and the measured data is within 3.2% and, thus, both values are in satisfactory agreement. However, according to Maubach's Equation for ciruclar tubes /16/:

$$1/\sqrt{\lambda} = 2.035\ \lg(Re\sqrt{\lambda}) - 0.989 \qquad (7)$$

the friction factor of a circular is calculated to

$$\lambda_R = 0.0196$$

The deviation between the experimental friction factor and that of a circular tube is 5.86%.

The relative average velocities in all parts of the region investigated raised to the power of 1.8 agree with the relative average wall shear stresses within 2.8% (see Table 9).

3.4 Turbulence Intensities and Turbulent Kinetic Energy

The distributions of the turbulence intensities and the kinetic energy are displayed with both linear plots along the traverses from the walls (scaled by the local friction velocity) and by contour plots. In the contour plots, the turbulent intensity was scaled by the friction velocity based on the wall shear stress on the rod wall at $\phi = 0°$ in quadrant 1.

3.4.1 Axial Turbulence Intensity

Figures 10-1 to 10-4 and Figs. 11-1 to 11-4 show the distributions of the axial turbulence intensity along the traverses from the rod walls (r/ϕ-part) and channel walls (x/y -part) in the four quadrants, respectively. The axial turbulence instensity is also shown in Fig. 12 as contours. The following characteristics are notable:

1. The axial turbulence intensity decreases with increasing distance from the walls in the rod gap area $\phi = 0°\text{-}35°$, $80°\text{-}90°$, and $x = 70\text{-}80$ mm, 0-15 mm. In the area near the walls, the axial intensity reaches relative high values of $\sqrt{\overline{u'^2}}/u^* = 2.0\text{-}2.4$, while on the line of maximum distance from the walls the minimum axial turbulence intensity was relatively low, only about 1.2.

2. In the area $\phi = 45°\text{-}70°$, $x = 30\text{-}60$ mm, the axial turbulence intensity changes slowly, it even keeps constant along the traverses.

3. In the area $\phi = 50°\text{-}65°$ and $x = 25\text{-}55$ mm, there exist regions with very strong axial turbulence intensity, which indicate a strong turbulent momentum transprot through the narrow gaps between rods and channel walls due to a large scale eddy motion /17/. A comparison of the above characteristics 1,2, and 3 of the experimental results (with a wider gap between rod and channel wall, W/D = 1.074) with the results of the previous experiment (with a narrow gap W/D = 1.045) /18/ shows that:

   a. Under the condition of a wider gap between rod and channel wall, the axial intensity distribution in the gap region changed from a flat distribution on the traverses to a declined distribution from the wall.

   b. The peak value of the axial intensity in the region with a very strong axial turbulence intensity decreases with increasing width of the gap between rod and channel wall (from 2.8 to 2.4).

4. The minimum axial turbulence intensity is located at the center of the subchannel, which is coincident with the location of the maximum time-mean velocity. Another relative maximum of the axial intensity appears near the gap of rods at $\phi = 25°$, which forms a saddle-point region of the turbulence intensity in this area.

5. The contour plots show a smooth, symmetric distribution of the axial turbulence intensity.

6. It can also be seen from Fig. 12a that the distribution of the axial turbulence intensity along the line of maximum nomal distance from the walls has a first small maximum at $\phi = 25°$. However, a very strong maximum appears at $\phi = 60°$.

3.4.2 Azimuthal Turbulence Intensity

Figures 13-1 to 13-4 and Figures 14-1 to 14-4 show the distribution of the measured azimuthal turbulence intensity along the traverses in the area near the rod walls (r/ϕ-part) and the channel walls (x/y-part) in the four quadrants, respectively.

In the area ϕ = 0-40°, x = 50-80 mm, the azimuthal turbulence intensity $\sqrt{w^2}/u^*$ is relatively low and decreases with increasing distance from the walls, while near the walls it is close the value on the wall of circular tubes. In the center part of the wall subchannel (x = 80 mm, ϕ = 0-35°, on the line of maximum distance from the walls), it reaches a minimum of 0.9. In the area ϕ = 45-90° and x = 0-45 mm, the azimuthal turbulence intensity is relatively high and almost independent on the distance from the walls. The azimuthal intensity reaches maximum values in the gaps between the rods and channel walls at ϕ = 85°-90°, x = 0-10 mm of $(\sqrt{\overline{w^2}}/U^*)_{max} = 2.0$. The strong turbulent momentum transport through narrow gaps between the rods and channel walls is demonstrated once more. But a comparison with the results of the previous experiment /18/ (with a narrower gap, W/D = 1.045), shows that the peak azimuthal turbulence intensity decreased from 3.0 to 2.0 with increasing width of the gap. The azimuthal turbulence intensity is also shown in Fig. 15 as a contour plot. The contour lines are perpendicular to the boundary line of the wall subchannel at the gap between rods. This indicates no significant turbulent momentum transport through the boundary between the two symmetric wall subchannels. A comparison with the contour plots of the azimuthal turbulence intensity in /7/ (Abb. 18) shows that the present results, especially in the boundary area of the wall subchannels, are significantly different from those in the previous experiment /7/ (with a geometrically asymmetric arrangement). Figure 15a shows a monotonous distribution of the azimuthal turbulence intensity along the line of maximum nomal distance from the walls. The maximum of the azimuthal turbulence intensity appears at ϕ = 90°.

3.4.3 Radial Turbulence Intensity

The experimental results of the radial turbulence intensity display a nonuniform distributions in some regions due to the uncertainty of the measurement. Especially in the gap region between the rod and channel walls the very small signal for the radial turbulence intensity is obtained by subtracting two large signals, due to the high levels of both the axial intensity and azimuthal intensity, respectively (see contour plot Fig. 18). But in the gap region between the rods, the contour plot of the radial turbulence intensity is resonable (see also Fig. 18a). Here, the axial and azimuthal components of the fluctuating velocity are relatively small (see Figs. 16-1 to 16-4 for the r/ϕ-parts near the rod walls and Figs. 17-1 to 17-4 for x/y-parts near the channel walls, respectively). Generally, the radial turbulence intensity decreases with increasing distance from the walls. It reaches a maximum in the area near the walls of

$$(\sqrt{\overline{v'^2}}/U^*)_{max} = 1.2$$

3.4.4 Turbulent Kinetic Energy

The experimental results of the turbulent kinetic energy

$$\overline{k'} = 1/2\,(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}), \tag{8}$$

scaled by the square of the local friction velocity for the linear plots, are shown for each traverse in the four quadrants in Figs. 19-1 to 19-4 (for the r/ϕ-parts) and in Figs. 20-1 to 20-4 (for the x/y-parts) . Figure 21 is a contour plot of the turbulent kinetic energy scaled by the square of the friction velocity based on the wall shear stress at $\phi = 0°$ in quadrant 1.

In the area near both the rod and channel walls, the relative kinetic energy on all traverses does not differ very much (about 4.5). However, it is higher than the value in circular tubes (4.0). The variation of the kinetic energy along the traverses depends on the circumferential position of the traverse on the walls. In the wide area of the wall subchannel ($\phi = 0°$-$40°$, x = 60-80 mm), the turbulent kinetic energy decreases with increasing distance from the walls. At the position on the line of maximum distance from the walls, it reaches a minimum of about 1.5. It is still higher than the value in a circular tube (1.0). Closer to the gap between the rod and channel walls, at ($\phi = 45°$-$90°$, x = 0-55 mm), the turbulent kinetic energy appears without significant variation along the traverses. In the narrow area of the subchannel ($\phi = 75°$-$90°$, x = 0-15 mm), the kinetic energy displays a slight decrease with increasing distance from the wall. This behaviour is quite different from that in the previous experiment /18/ (with a narrower gap width, P/D = 1.045). On the line of maximum distance from the walls, it reaches values of about 4.5 in the linear plots. The turbulent kinetic energy displays a smooth and symmetric distribution on the contour plot (Fig. 21). It is clear, that in the four symmetric areas of $\phi = 55°\text{-}65°$ and $x = 35\text{-}50$ mm, there are four regions of strong kinetic energy formed by the turbulent momentum transport through narrow gaps between rods and channel walls. However, the peak value of the strong turbulence kinetic energy is significantly less than that in the previous experiment /18/ (with a narrower gap width), 4.5 against 6.5. It clearly reveals the influence of the gap width on the structure of turbulent flow in the gap region. Figure 21a shows the distribution of the turbulent kinetic energy along the line of maximum distance from the wall for quadrant 1 to quadrant 4. It can also be clearly seen from Fig. 21a that at the position of $\phi = 60°$ a very strong maximum of the kinetic energy appears, which is coincident with the maximum of the axial turbulence intensity (see above section 3.4.1).

3.5 Turbulent Shear Stress and Correlation Coefficient

3.5.1 Azimuthal Turbulence Shear Stress $-\overline{u'w'}$

The experimental results of the azimuthal shear stress along the traverses scaled by the square of the local friction velocity are shown in Figs. 22-1 to 22-4 in linear plots for the r/ϕ-part and in Figs. 23-1 to 23-4 in linear plots for the x/y-part in the four quadrants, respectively. In the area near both the rod and channel walls, the azimuthal turbulent shear stresses decrease to zero. On several traverses, the azimuthal shear stresses are all close to zero. This is found on the traverses located between $\phi = 0°$ (the boundary between the symmetrical wall subchannels) and $\phi = 35°$ (the widest traverse), in the gap between the rods and the channel wall at $\phi = 90°$ and at $x = 0$ mm, and for $x = 75\text{-}80$ mm, i.e. on the symmetry line. For all the traverses mentioned above, the gradient of the mean velocity in the azimuthal direction is close to zero. In the contour plot of the mean velocity, Fig. 5, it is clearly shown that the contours in these areas are almost parallel to the rod walls (in the r/ϕ-part) or the channel walls (in the x/y-part). On the other traverses, the azimuthal turbulent shear stresses increase to varying degrees with increasing distance from the walls. In the area of $x = 20\text{-}40$ mm and $\phi = 60°\text{-}75°$, respectively, the azimuthal shear stresses reach maximum values of about: $-\overline{u'w'}/u^{*2} = 2.4$. Compared with the previous experiment /18/ (with a narrower gap width, W/D = 1.045), the peak value of the azimuthal shear stress also significantly decreases from 4.0 to 2.4. The four symmetrical regions of the maximum values of the azimuthal shear stress near the gaps between rods and channel walls are clearly displayed in the contour plot of the azimuthal shear stress (see Fig. 24). In the area near the gap between the rods, there exists a relatively wide region of zero azimuthal shear stress (also on Fig. 24).

3.5.2 Shear Stress Perpendicular to the Walls $-\overline{u'v'}$

The measured distributions of the normal shear stress (the shear stress perpendicular to the walls) along the traverses scaled by the square of local friction velocity are shown in Figs. 25-1 to 25-4 for the r/ϕ-parts and in Figs. 26-1 to 26-4 for the x/y-parts of the four quadrants. Generally, the normal shear stresses decrease almost linearly with increasing distance from the walls. In the area near the walls, the normal shear stresses are very close each other and also close to the value on the wall of circular tubes (1.0) on all traverses.

In the area of $\phi = 0°\text{-}40°$, $\phi = 80°\text{-}90°$, x = 0-15 mm, and x = 70-80 mm, the distributions of the normal shear stresses along the traverses in the subchannel of the rod bundle agree with that in circular tubes perfectly. But in the rest area, the normal shear stresses in the subchannel of rod bundles are always considerably higher than that in circular tubes.

3.5.3 Transverse Shear Stress $-\overline{v'w'}$

In this experiment, the distributions of the transverse turbulent shear stresses were also measured. The results (shown in Figs. 27-1 to 27-4 for the r/ϕ-parts and Figs. 28-1 to 28-4 for the x/y-parts) scaled by the square of the local friction velocity relatively scatter away from zero. Whereas, in the areas near the walls, the measurement results are close to zero, in the area far away from the walls, the results scatter even more. Generally, a definite regularity of the distribution of the trasverse shear stress cannot be found from the measurements because of the uncertainty in measuring small signals.

3.5.4 Correlation Coefficient R_{uv}

The experimental results of the distributions of the correlation coefficient in the direction perpendicular to the walls are described by

$$R_{uv} = \frac{-\overline{u'v'}}{\sqrt{\overline{u'^2}} \cdot \sqrt{\overline{v'^2}}} \tag{9}$$

and shown in Figs. 29-1 to 29-4 for the r/ϕ-parts and in Figs. 30-1 to 30-4 for the x/y-parts of the four quadrants. In a relative wide region, the correlation coefficient R_{uv} is about 0.4. In the area near the walls, the values of the correlation coefficient are close to each other. The correlation coefficients decrease with increasing distance from the walls and tend to zero at the position near the line of maximum distance from the walls. This variation is similar to that in circular tubes. In the area of x = 15-45 mm and $\phi = 60°$-$80°$ (the gap region between the rods and the channel walls), the experimental results of the correlation coefficient are unreasonably much higher and scattered. This is caused by the very small radial turbulence intensity and its uncertainty of measurement in these areas.

3.5.5 Correlation Coefficient R_{uw}

The experimental results of the correlation coefficients of the shear stress parallel to the walls are described by:

$$R_{uw} = \frac{-\overline{u'w'}}{\sqrt{\overline{u'^2}} \cdot \sqrt{\overline{w'^2}}} \tag{10}$$

and shown in Figs. 31-1 to 31-4 for the r/ϕ-parts and in Figs. 32-1 to 32-4 for the x/y-parts of the four quadrants. In Fig. 33, the results are also presented as a contour plot.

The following characteristics can be observed:

1. The distribution of the correlation coefficient parallel to the walls R_{uw} agrees very well with the distribution of the azimuthal shear stress. Four regions of maximum value are displayed at the symmetrical positions in the gap areas between the rod and channel walls (x = 20-50 mm, $\phi = 50°$-$75°$). The maximum of the correlation coefficient R_{uw} is about 0.7.

2. On several traverses ($\phi = 0°$-$30°$, $\phi = 90°$, x = 0, x = 80 mm) the correlation coefficient R_{uw} is close to zero.

3. Close to both the rod and channel walls, the correlation coefficients R_{uw} tend towards zero. But they increase with increasing distance from the walls along the traverses (except for the traverses mentioned above (2)).

4. Compared with the previous experiment /7/, the distribution of the correlation coefficient R_{vw} in the gap region between the rods in the present experiment is quite different from that in /7/, which reveals the influence of geometrical symmetry on the distribution of the correlation coefficient R_{uw} once more.

3.5.6 Correlation Coefficient R_{vw}

The distribution of the correlation coefficient R_{vw} scatters about zero and is distributed within a narrow range of ± 0.2 in most of the area of the four quadrants (see Figs. 34-1 to 34-4 for the r/ϕ-parts and Figs. 35-1 to 35-4 for the x/y-parts of the four quadrants). But there are also some data scattered away within a wider range due to the measurement uncertainty of small signals.

3.6 Difference of Turbulence Intensity Parallel and Perpendicular to the Walls

A finite gradient of the difference in the turbulent normal stresses in the plane of the channel cross section in the peripheral direction is considered as a driving force for the secondary flow in the plane of the channel cross section. And the normal stresses only are significant in secondary flow production /20/.

In this investigation, the distribution of the difference of the turbulence intensities $(\overline{w'^2}-\overline{v'^2})$ was measured. The results scaled by the square of local friction velocity are shown in Figs. 36-1 to 36-4 for the r/ϕ-parts and in Figs. 37-1 to 37-4 for the x/y-parts of the four quadrants.

1. In the gap region between the rods and the channel walls ($x = 0$-40 mm, $\phi = 55°$-$90°$), the difference of the turbulence intensities $(\overline{w'^2}-\overline{v'^2})$ is relatively high due to the very high azimuthal intensity and the low radial intensity. Directly in the gap between the rods and channel walls, it reaches maximum values of $(\overline{w'^2}-\overline{v'^2}) = 4.0$. But it is much less than that in the previous experiment /18/ (with a narrower gap $W/D = 1.045$). And in this area, the difference of the turbulence intensities increases with increasing distance from the walls, while it varies greatly in the peripheral direction.

2. In the gap region between rods ($\phi = 0\text{-}50°$, $x = 45\text{-}80mm$), the difference of the turbulence intensities is relatively low. And it varies slowly in peripheral direction.

3. In the area near the walls, the peripheral gradient of the difference of the turbulence intensities is small. It increases with increasing distance from the walls. The maximum gradient of the difference of the turbulence intensities appears on the line of maximum normal distance from the walls.

Figure 38 shows a contour plot of the difference between the intensities parallel and normal to the walls.

4. Comparisons Between the Experimental Wall Shear Stresses and the Predictions by the VELASCO code

The distributions of the mean velocities and of the wall shear stresses have been computed by the VELASCO code /21/ for the wall subchannels of this experiment (P/D = 1.148, W/D = 1.074). The calculated wall shear stresses are shown in Fig. 39 together with the experimental data. All results are related to the average wall shear stress of the four quadrants. The plot on the top of the figure displays the data for the channel walls whereas the plot at the bottom shows the data along the rod walls.

As observed in the previous experiment /7/, the variations of the wall shear stresses predicted by VELASCO are much more pronounced as the experimental results. Especially in the gaps between the rods and the channel walls, the calculated wall shear stresses are about 25% lower than the experimental results. The main reason for this deviation is the cyclic momentum transport between neighbouring subchannels not modelled in the code. In the gap between the rods, the computed results are much higher than the experimental data. But by comparison with the result of /18/ (with a narrower gap, W/D = 1.045), the predicted results for the present geometry are closer to the experimental data due to the wider gaps between the rods and channel walls. The comparison shows that the VELASCO code based on experimental results in circular tubes and annuli is not suited for the analysis of rod bundles with narrow gaps between the rods and the rods and channel walls, respectively. Turbulent flow through rod bundles is different from turbulent flow through tubes and annuli.

5. Conclusions

1. The comparison between the measurements in a rectangular channel with a symmetrically arranged rod bundle and in an asymmetrical wall subchannel indicates that:

   a. for the symmetrical arrangement, the momentum transport through the rod gap disappears, and therefore

   b. the friction factors based on the measurement of the wall shear stress and on the measurement of the pressure drop agree very well in all quadrants

   c. the distributions of the time mean velocity, the wall shear stress, and the turbulent structure in the gap area between rods are quite different from that in an asymmetrical arrangement

   d. the experimental results of the turbulence intensities, the turbulent shear stress, and the turbulent kinetic energy indicate once more a strong turbulent momentum transport through the narrows gaps between rods and channel walls.

2. Compared with the previous experiment /18/ (with a narrower gap between rods and channel walls, W/D = 1.045), in this investigation (with the wider gap, W/D = 1.074), the influence of the gap width between the rods and channel walls on the structure of turbulence is smaller.

3. The comparison with calculated results by VELASCO shows that the turbulent flow through rod bundles is different from turbulent flow through tubes and annuli, the basis of the models of VELASCO. The VELASCO code is not well suited for the analysis of turbulent flow through rod bundles with narrow gaps.

ACKNOWLEDGMENT

The authors thank Mr. G. Wörner for this cooperation in performing the experiments and in evaluation of the results.

Nomenclature:

a	m	Distance
A	-	Geometry parameter
D	m	Rod diameter
D_h	m	Hydraulic diameter
G^*	-	Geometry parameter
K	-	Geometry parameter
$\overline{k'}$	$m^2 \cdot s^{-2}$	Turbulent kinetic energy
L	m	Distance between walls and the line of maximum normal distance from the wall
P	m	Distance between rods
p	Pa	Pressure
r	m	Radius
R_{uv}	-	Correlation coefficient of uv
R_{uw}	-	Correlation coefficient of uw
R_{vw}	-	Correlation coefficient of vw
Re	-	Reynolds number
T	°C	Temperature
U	ms^{-1}	Velocity in axial direction
u'	ms^{-1}	Turbulent velocity in axial diraction
U_{REF}	ms^{-1}	Reference velocity
U_m	ms^{-1}	Average velocity
U^*	ms^{-1}	Friction velocity

U^+	-	Dimensionless velocity
v'	ms^{-1}	Turbulent velocity normal to the wall
W	m	Distance between rod and channel wall
w'	ms^{-1}	Turbulent velocity parallel to the wall
x	m	Position along the channel wall
y	m	Distance from the wall
y^+	-	Dimensionless distance from the wall
λ	-	Friction Coefficient
ϕ	deg	Angle Coordinate
ρ	Kgm^{-3}	Density
ν	m^2s^{-1}	Kinematic viscosity
τ_w	Nm^{-2}	Wall shear stress
τ_{wm}	Nm^{-2}	Average wall shear stress
Δ	-	Discrepancy

Indices

r	Radial
ϕ	Angle in the direction along the rod wall
th	Theory
av	Average

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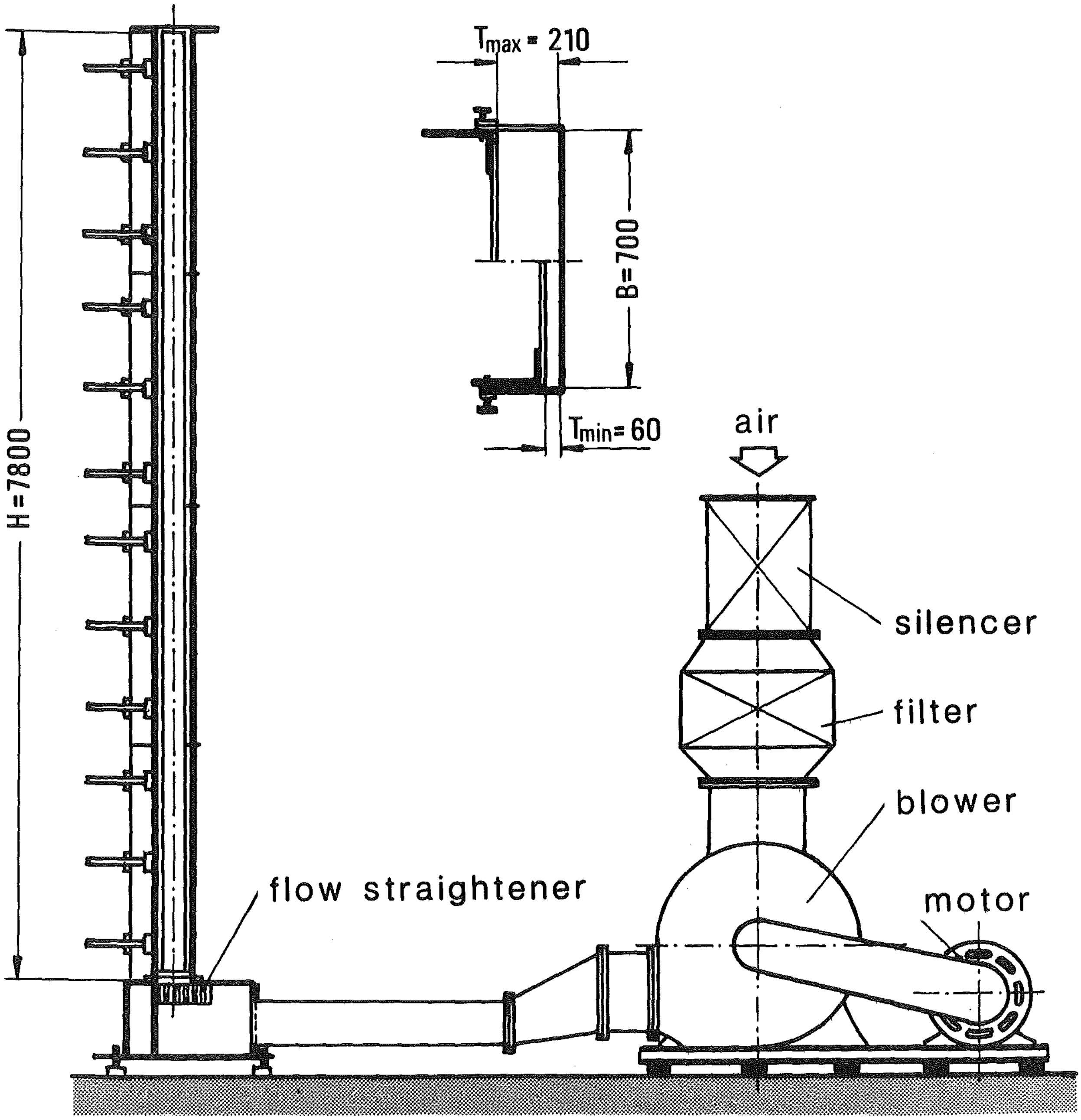
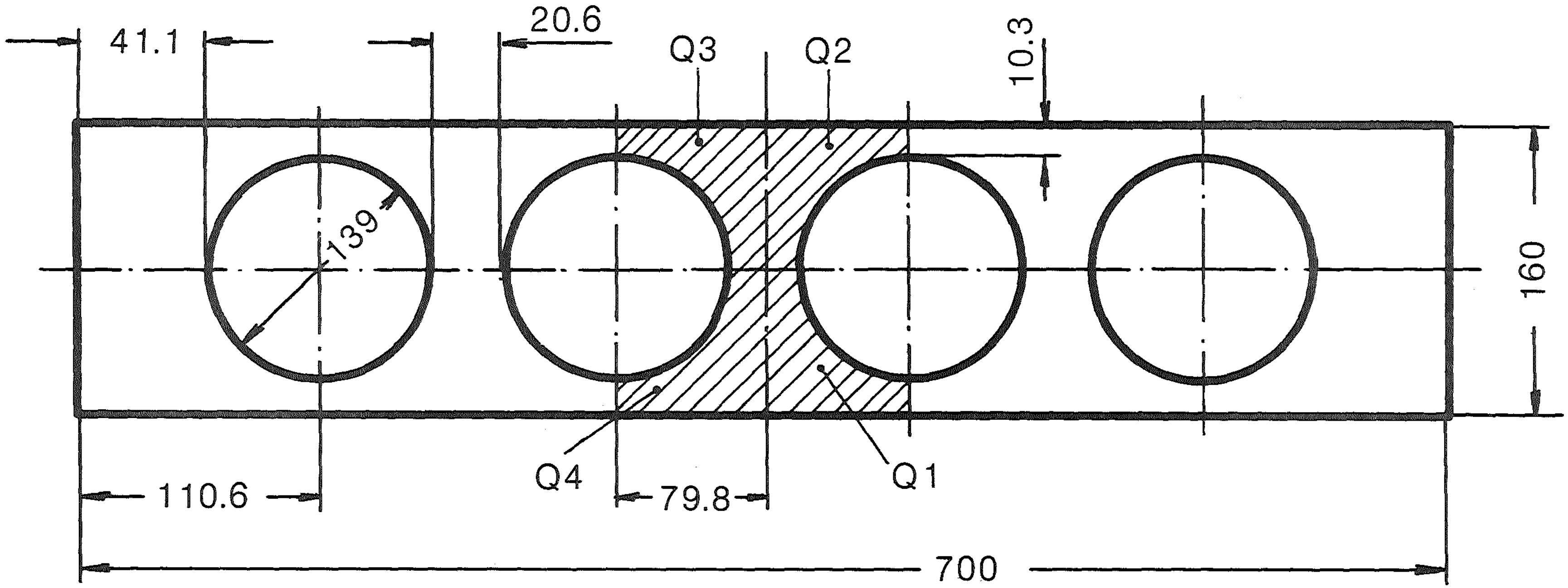


Fig. 1 Schematic of the test rig



P/D=1.148

W/D=1.074

Fig. 2 Cross section of the test section

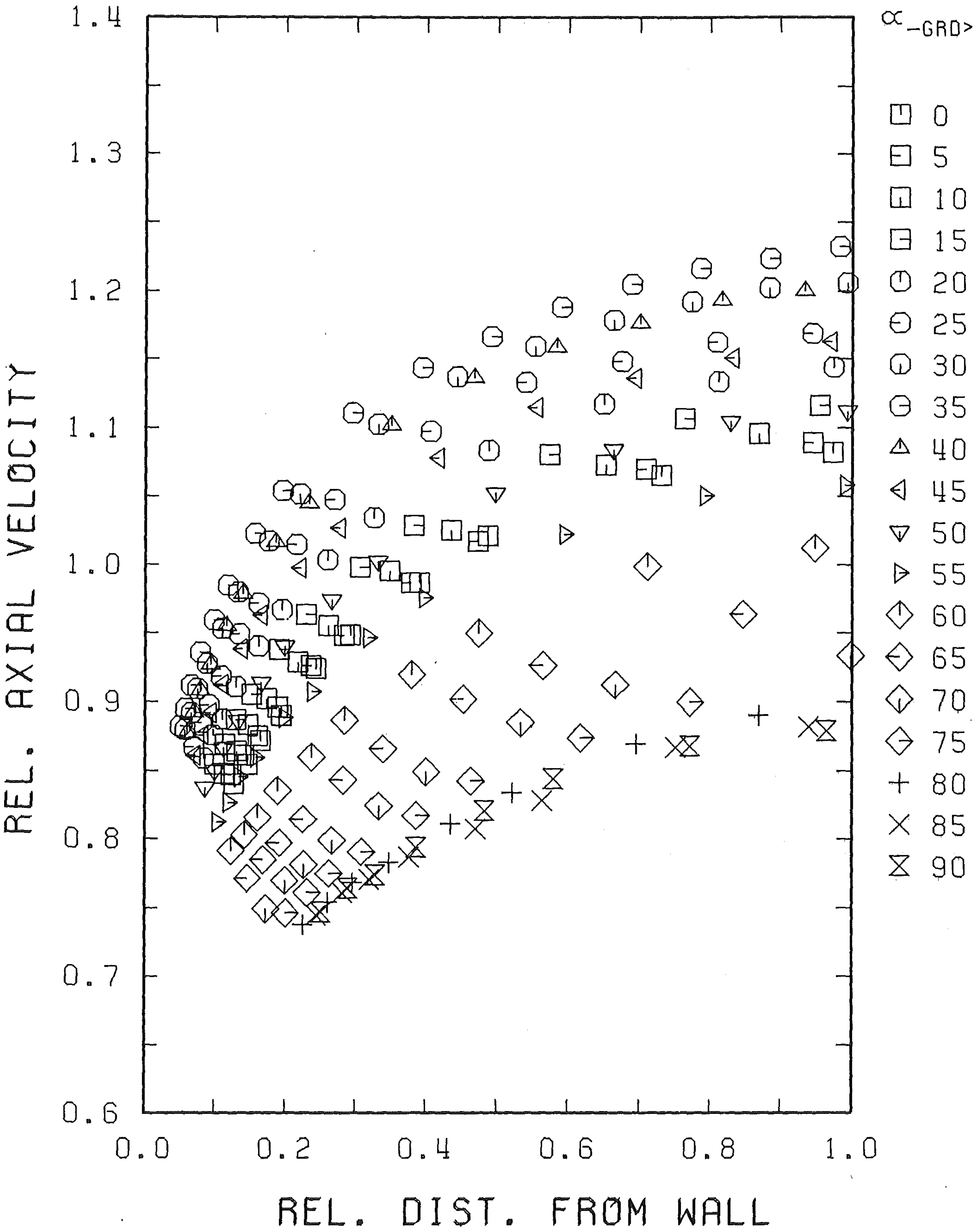


Fig. 3-1 Distribution of axial velocity in the r/ϕ-part of quadrant 1

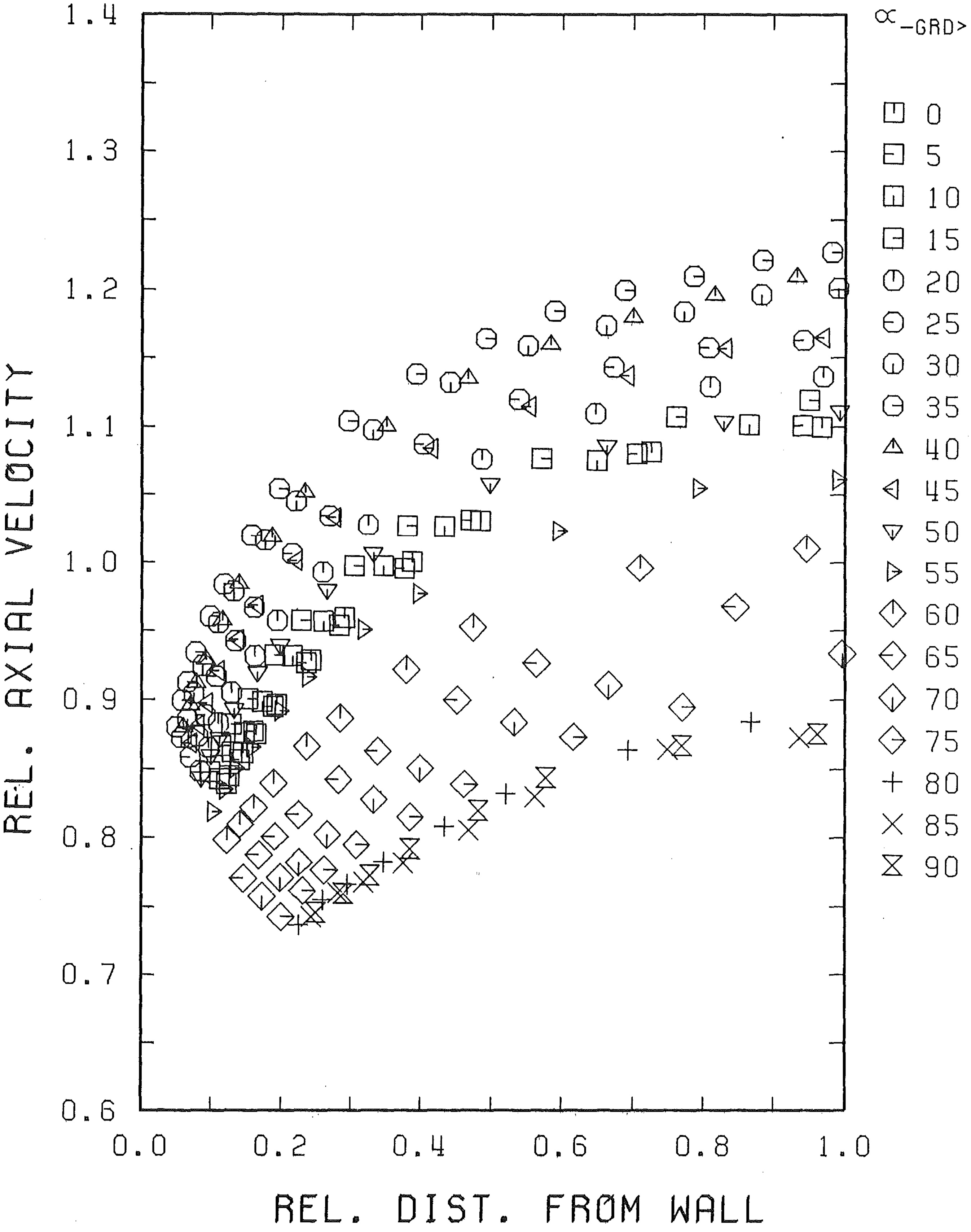


Fig. 3-2 Distribution of axial velocity in the r/ϕ-part of quadrant 2

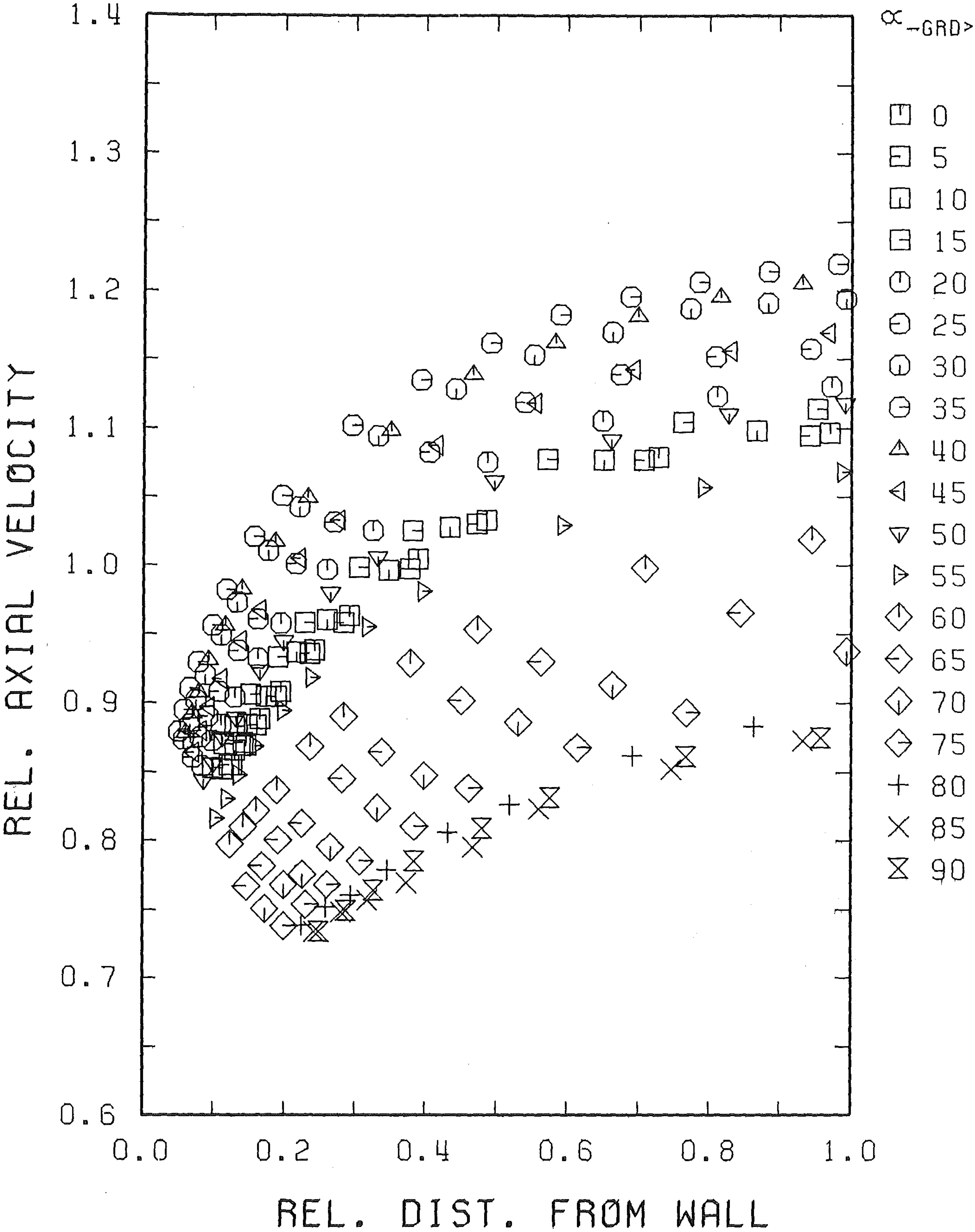


Fig. 3-3 Distribution of axial velocity in the r/ϕ-part of quadrant 3

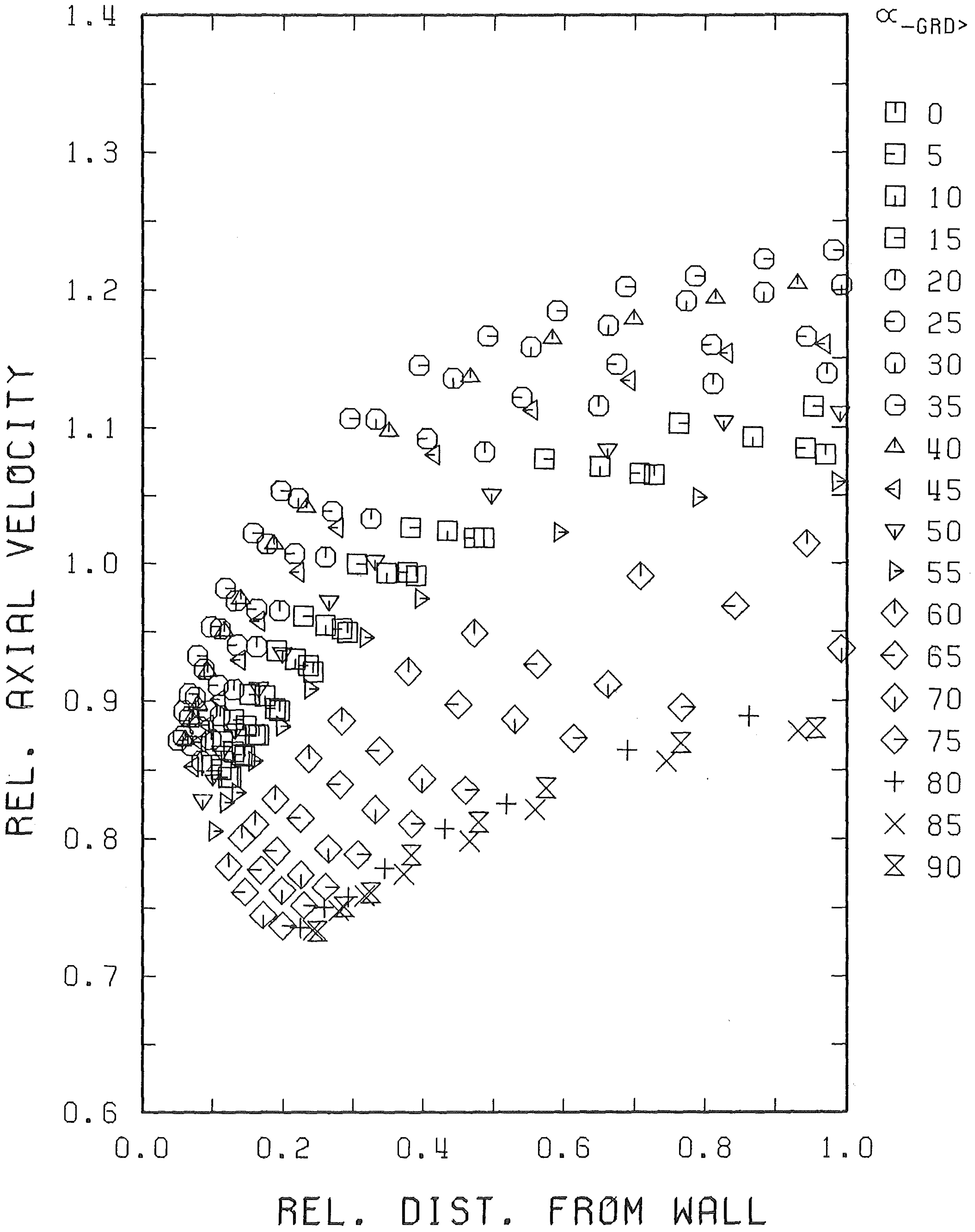


Fig. 3-4 Distribution of axial velocity in the r/ϕ-part of quadrant 4

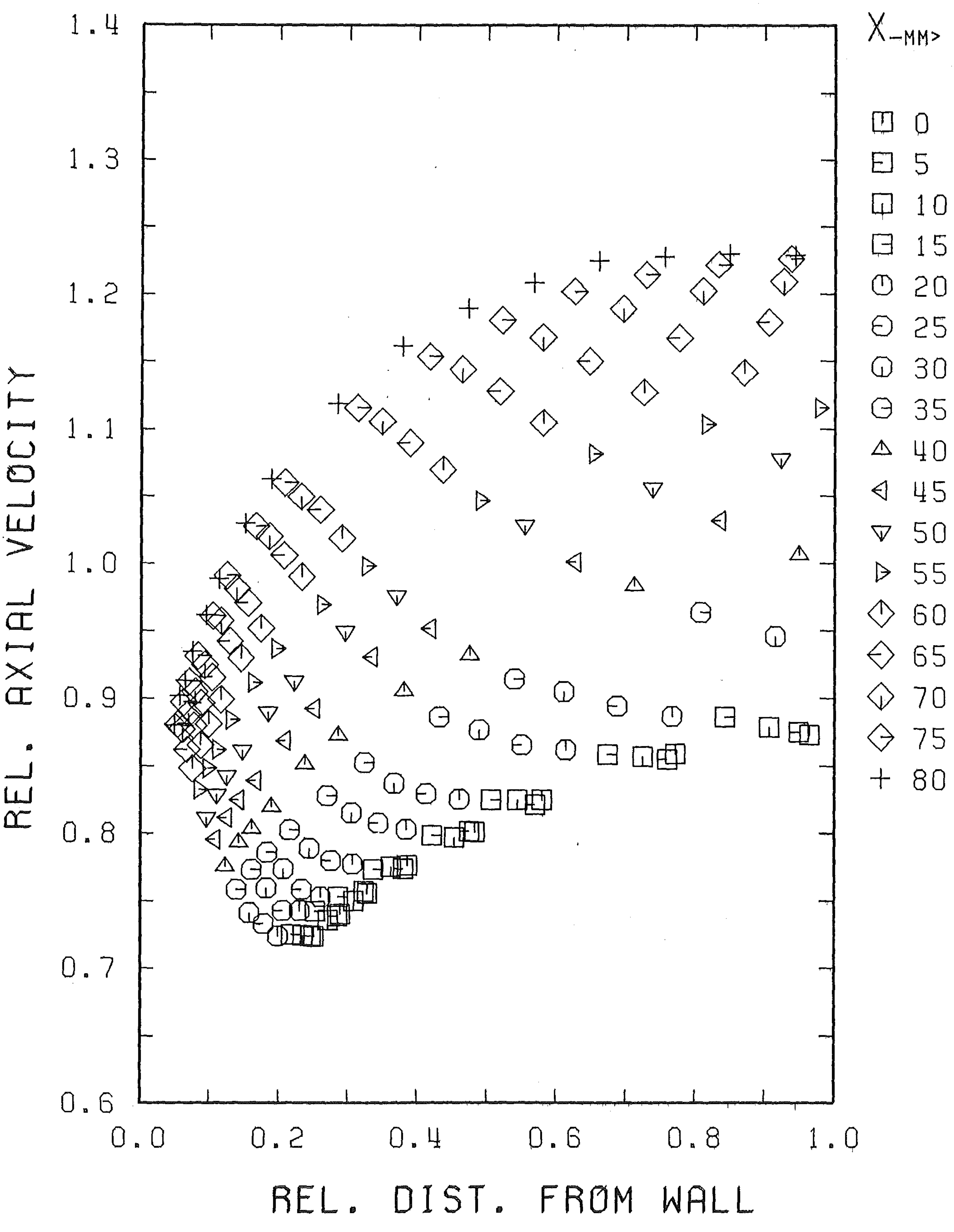


Fig. 4-1 Distribution of axial velocity in the x/y-part of quadrant 1

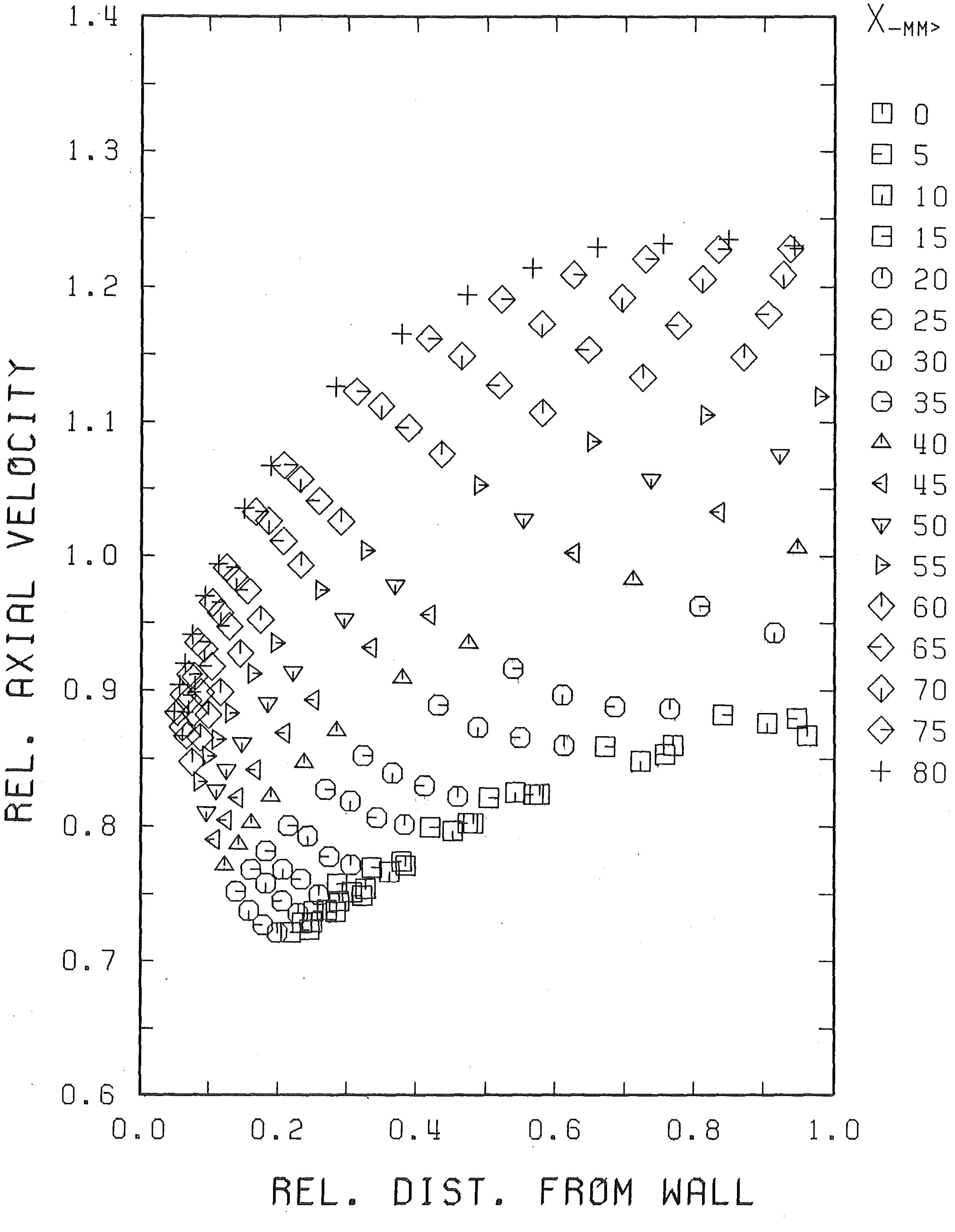


Fig. 4-2 Distribution of axial velocity in the x/y-part of quadrant 2

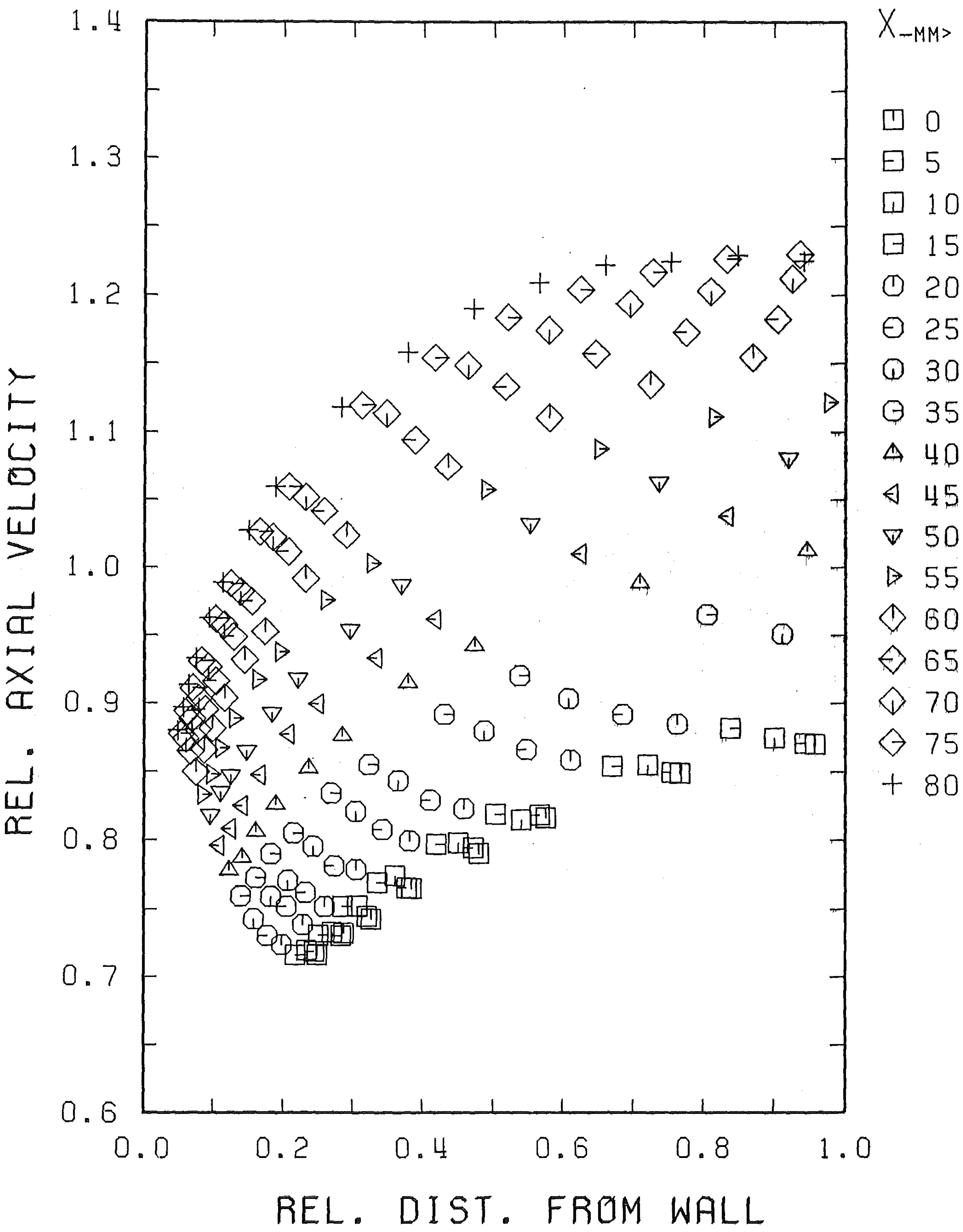


Fig. 4-3 Distribution of axial velocity in the x/y-part of quadrant 3

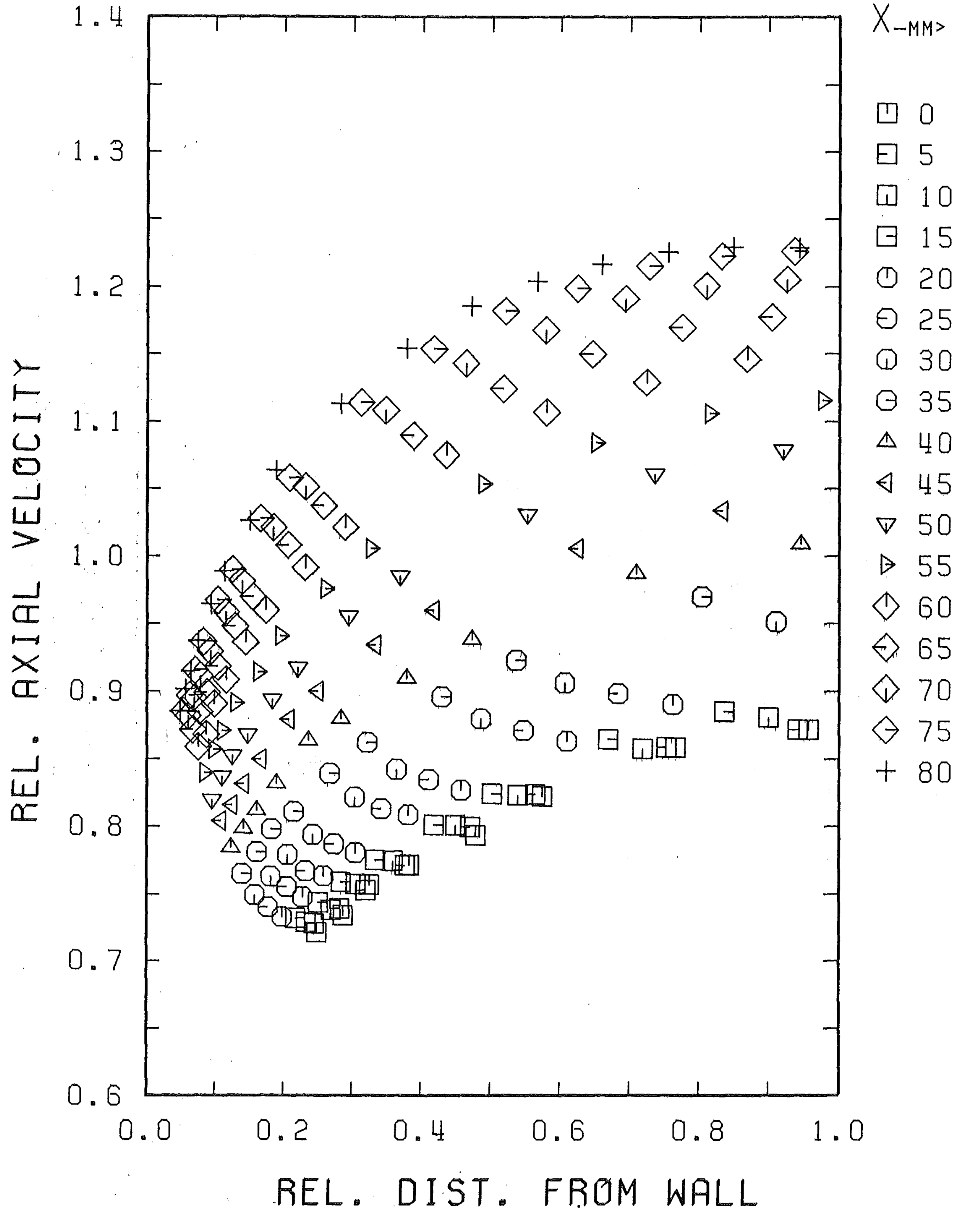


Fig. 4-4 Distribution of axial velocity in the x/y-part of quadrant 4

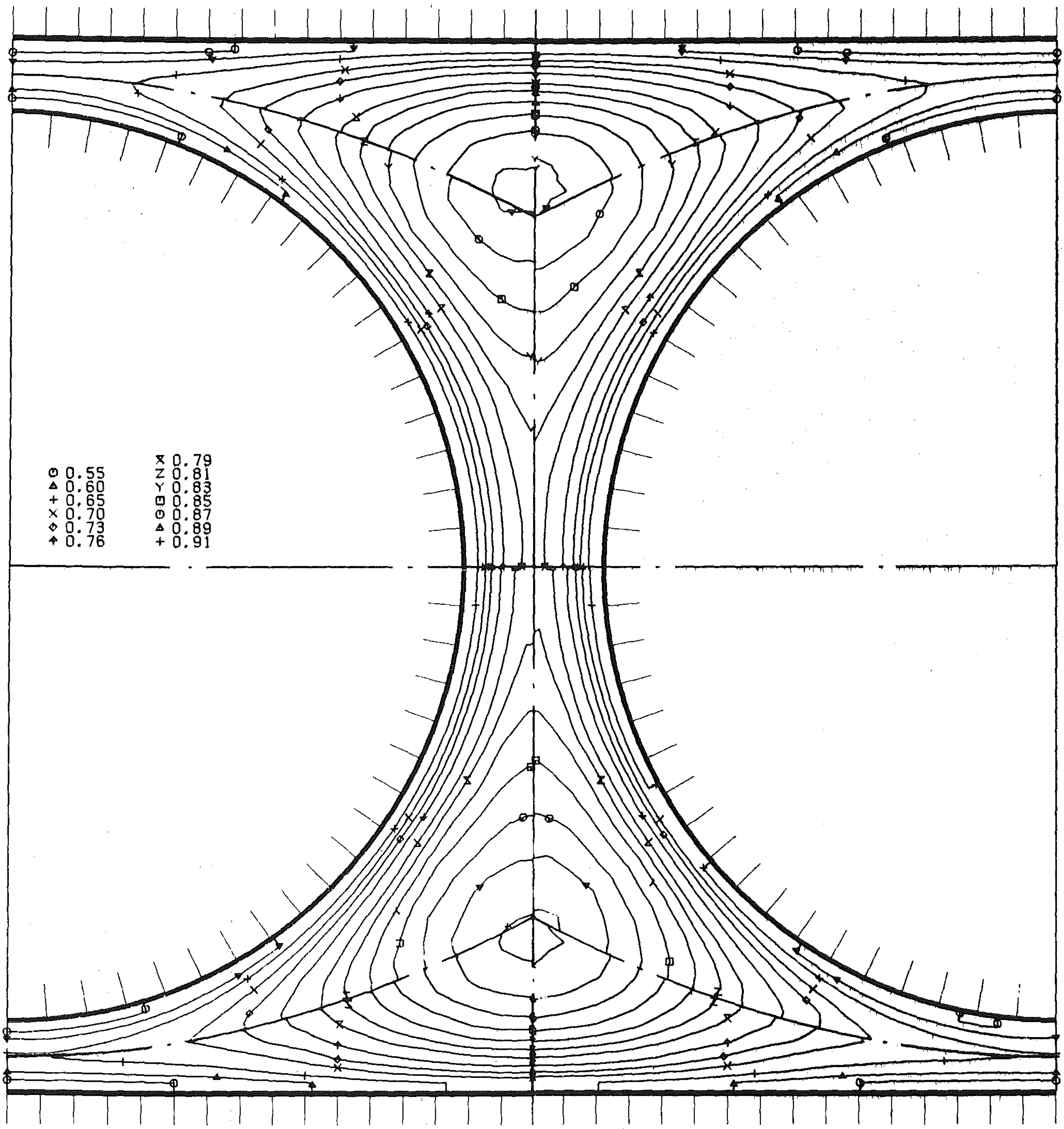


Fig. 5 Contours of axial velocity in the four quadrants

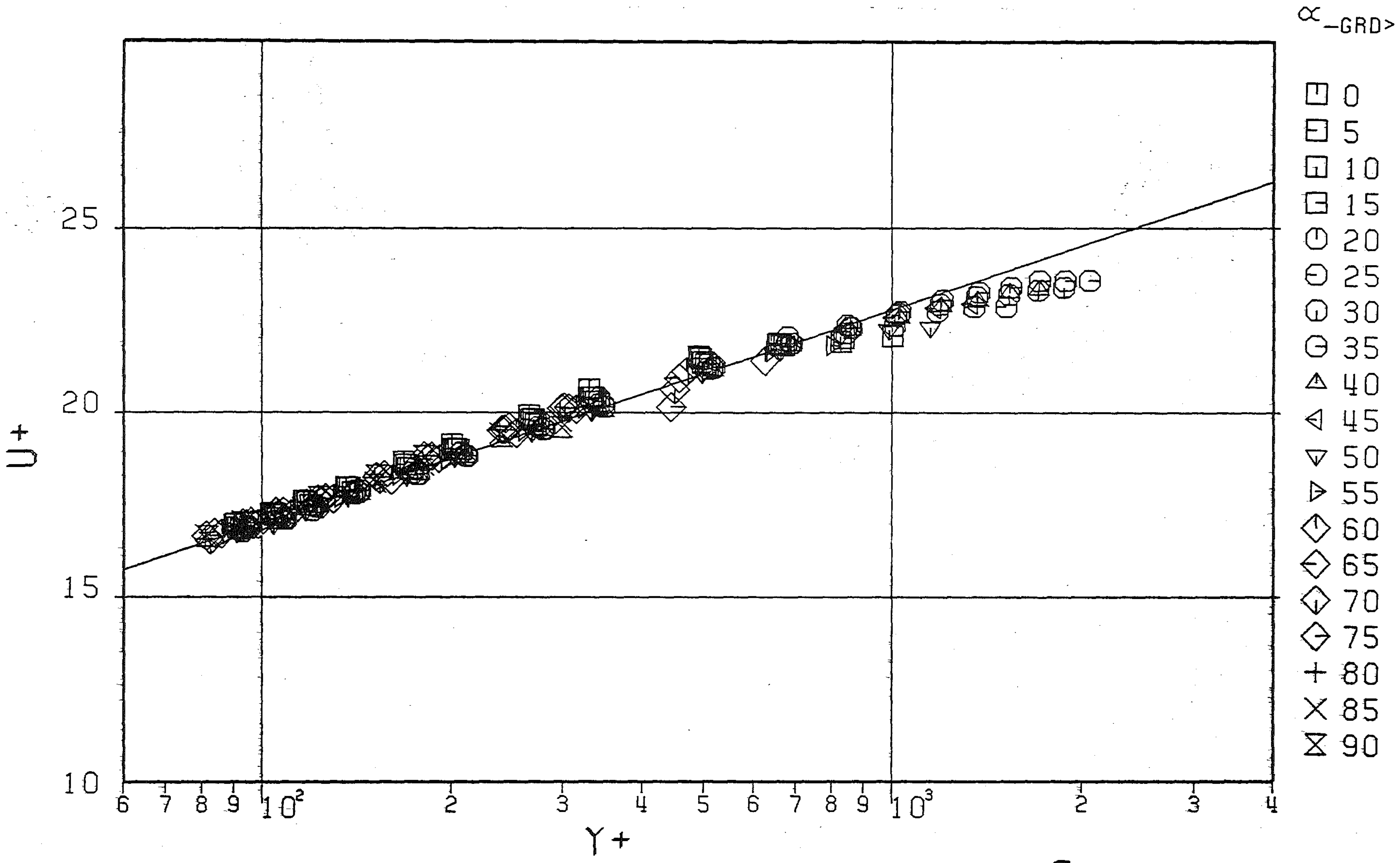


Fig. 6-1 Distribution of dimensionless velocity in the r/ϕ-part of quadrant 1

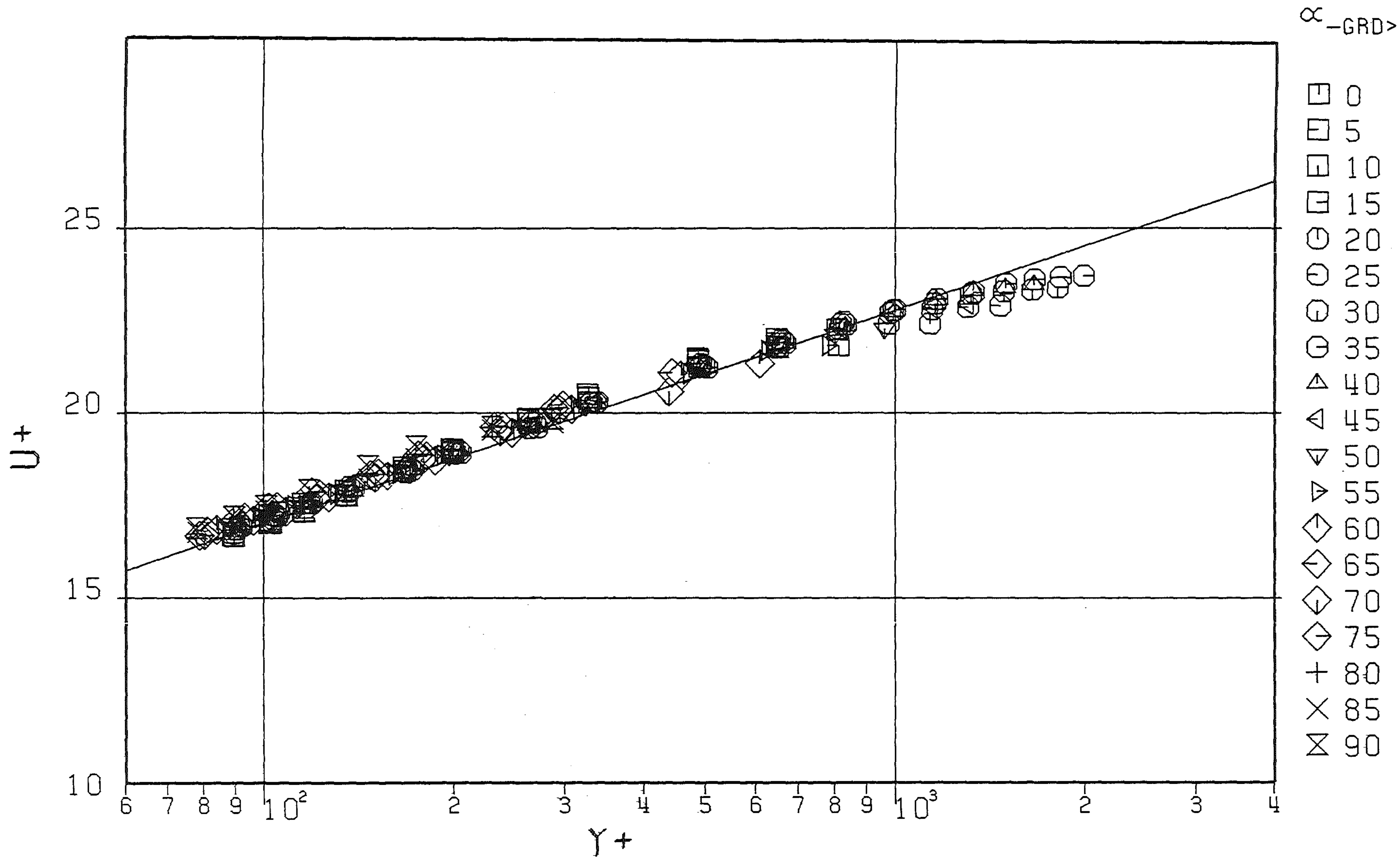


Fig. 6-2 Distribution of dimensionless velocity in the r/ϕ-part of quadrant 2

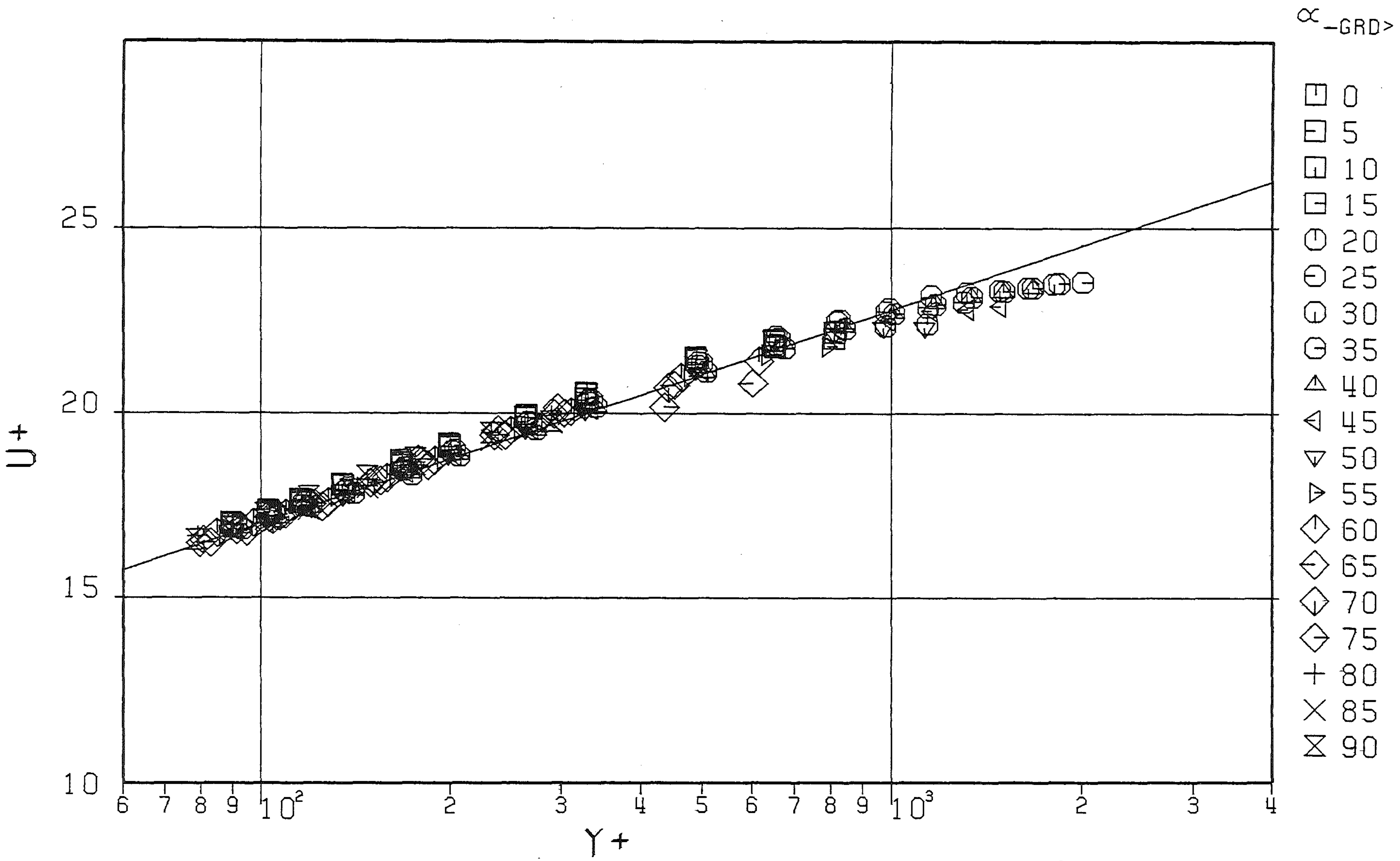


Fig. 6-3 Distribution of dimensionless velocity in the r/ϕ-part of quadrant 3

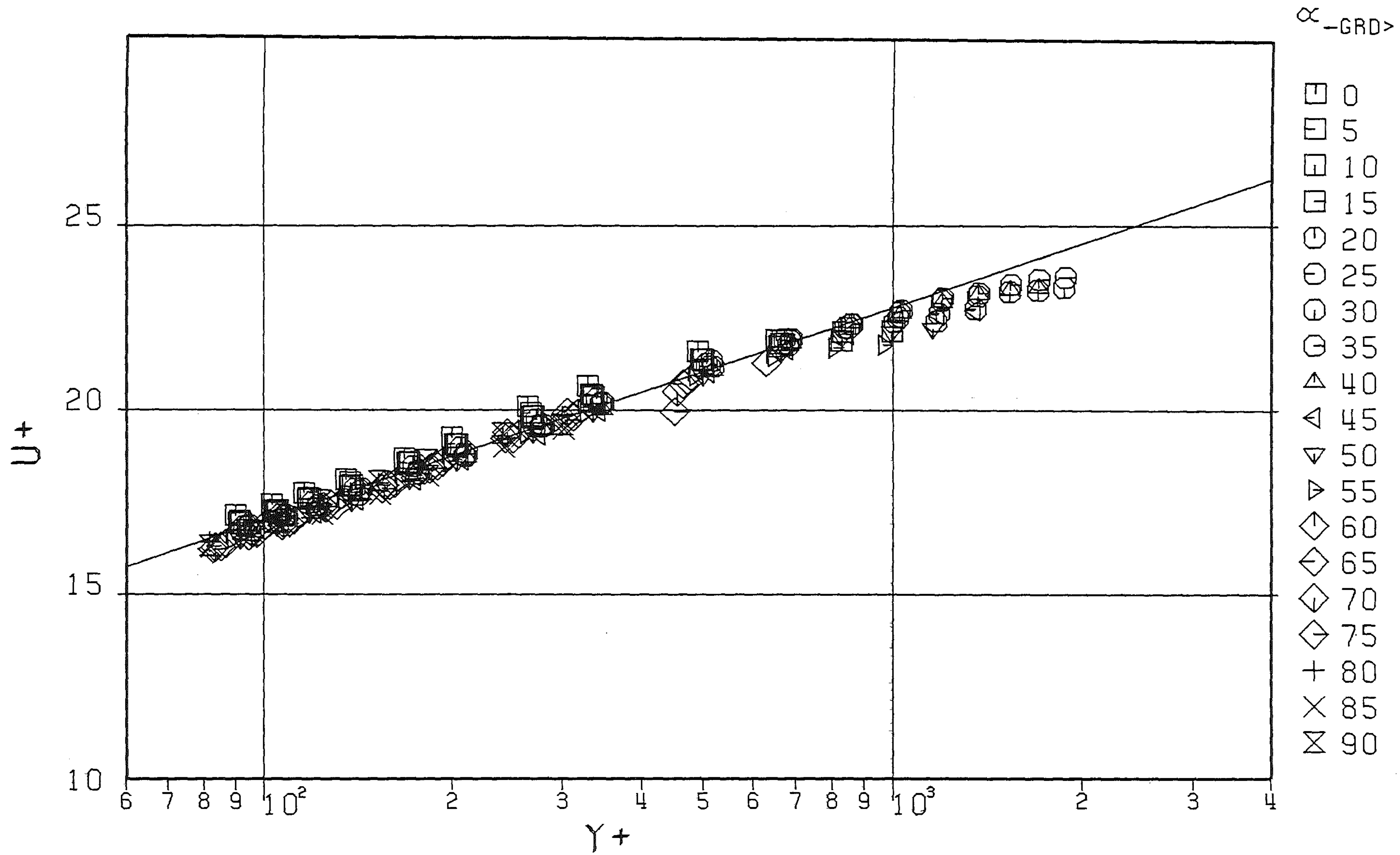


Fig. 6-4 Distribution of dimensionless velocity in the r/ϕ-part of quadrant 4

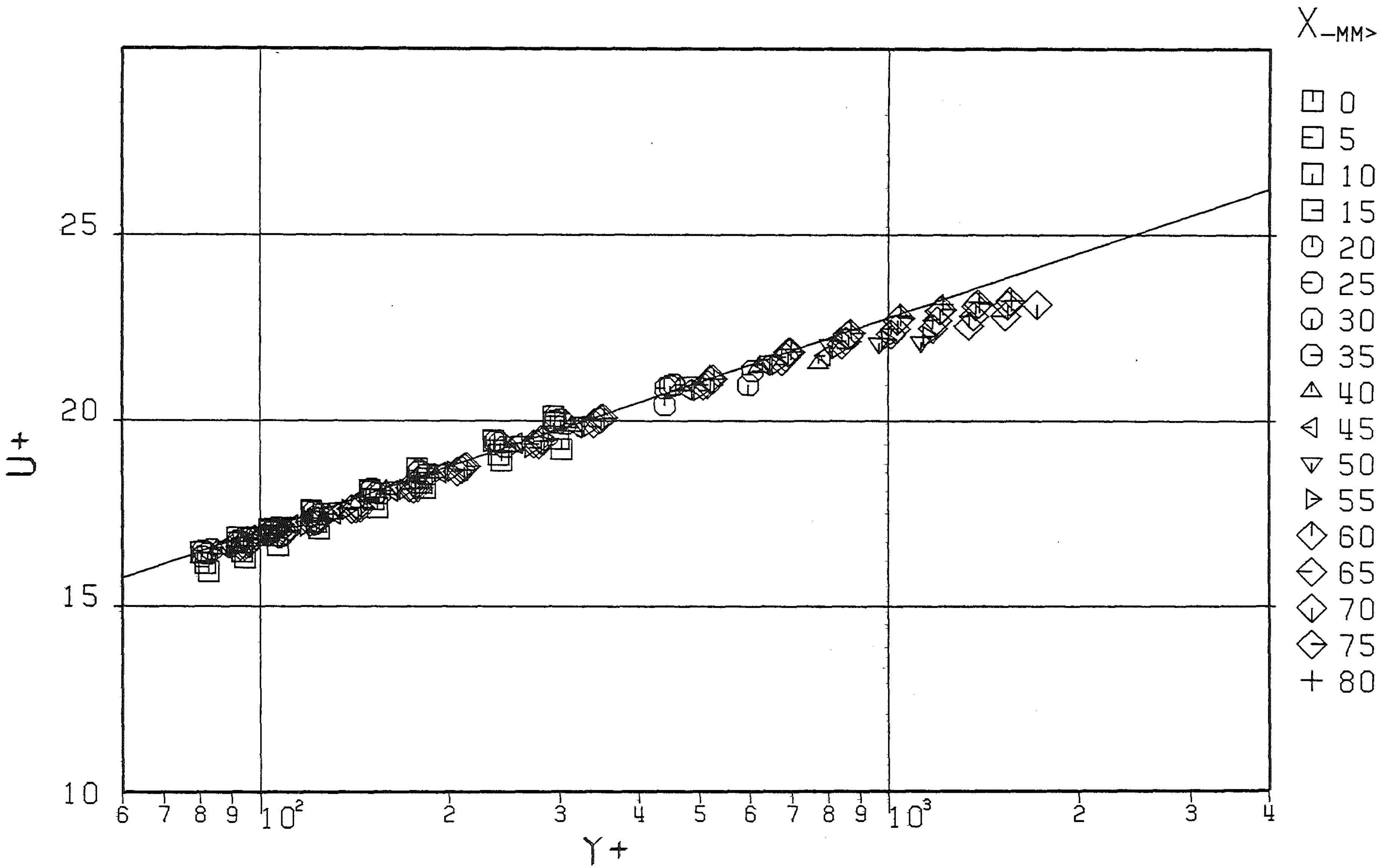


Fig. 7-1 Distribution of dimensionless velocity in the x/y-part of quadrant 1

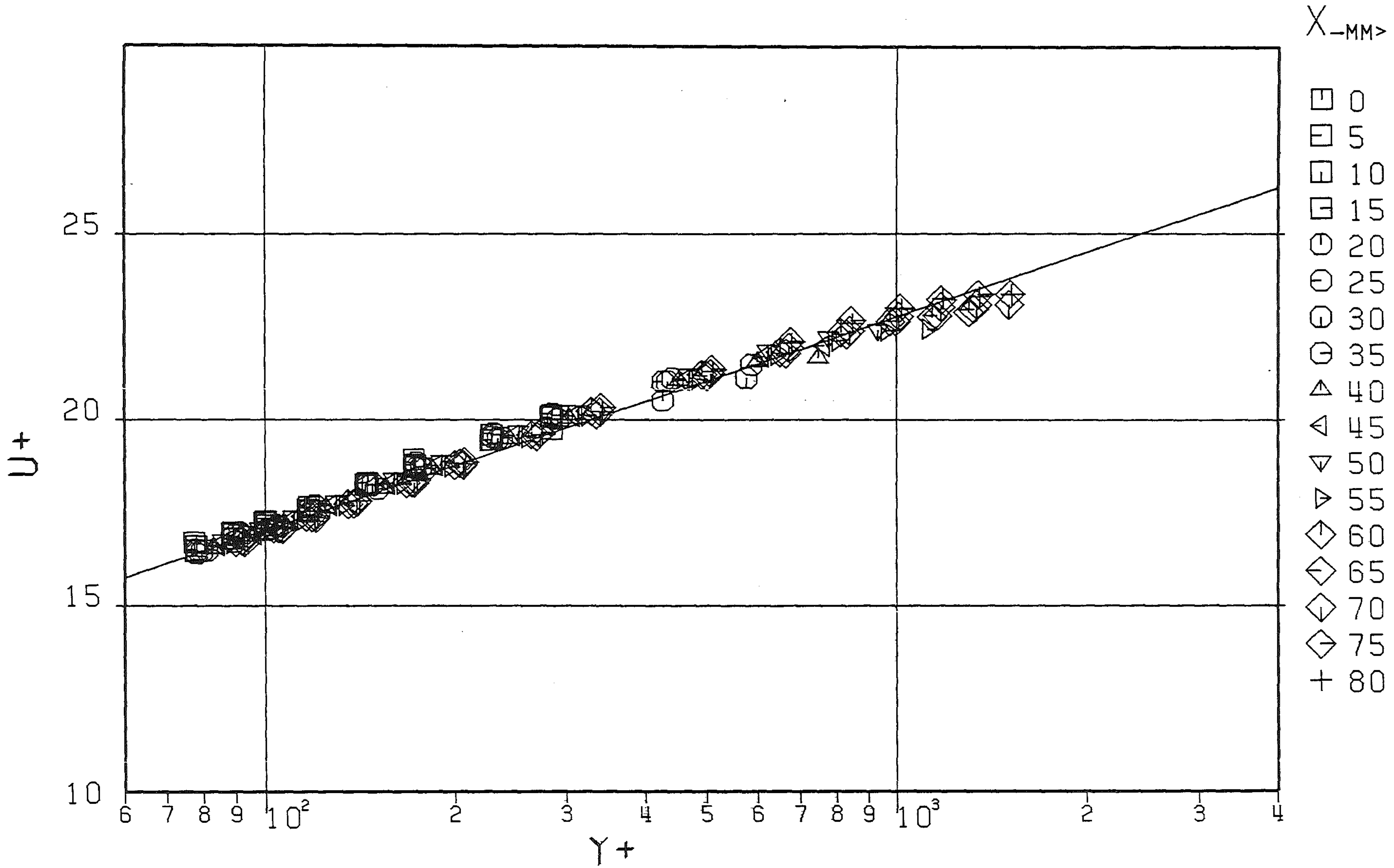


Fig. 7-2 Distribution of dimensionless velocity in the x/y-part of quadrant 2

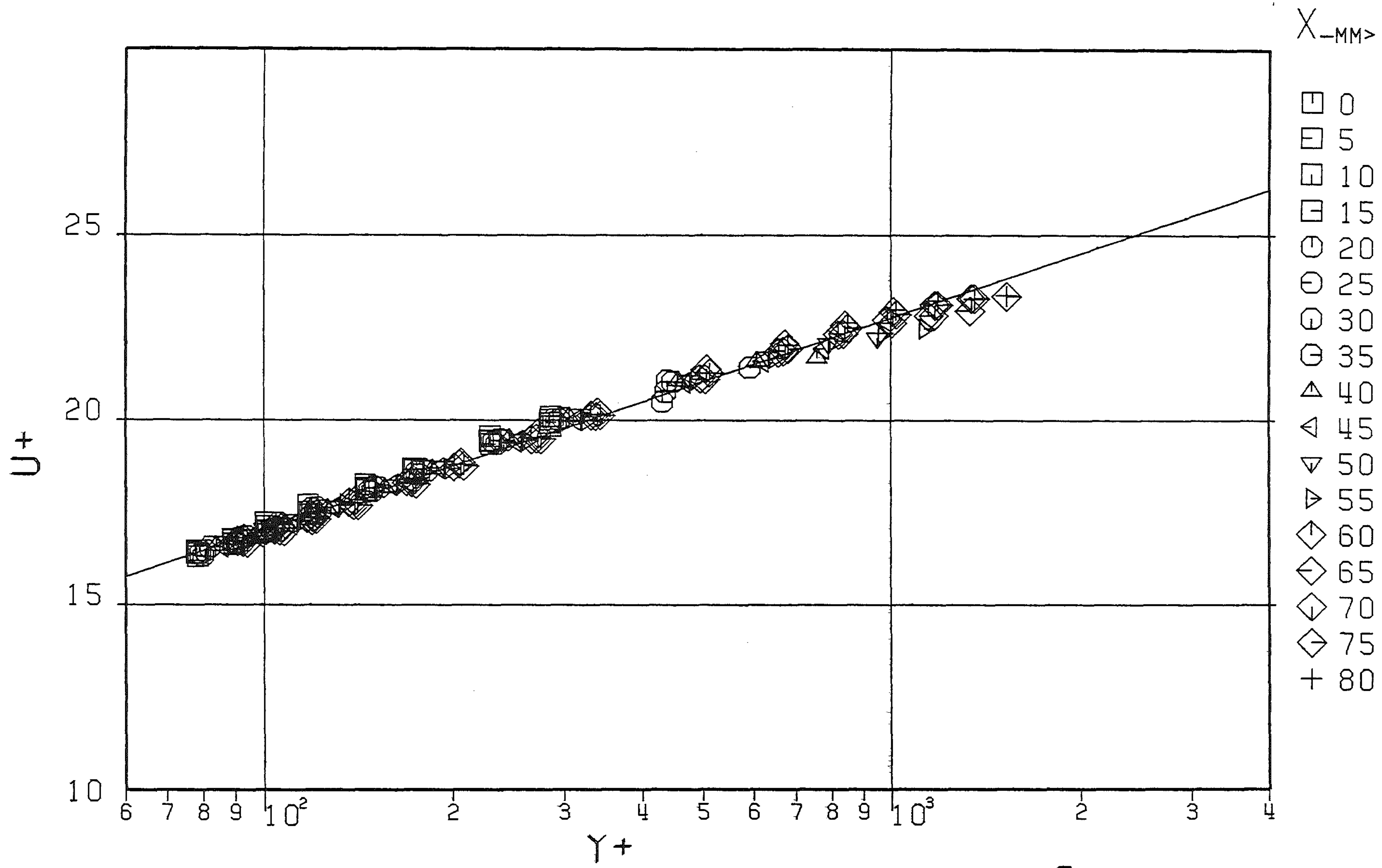


Fig. 7-3 Distribution of dimensionless velocity in the x/y-part of quadrant 3

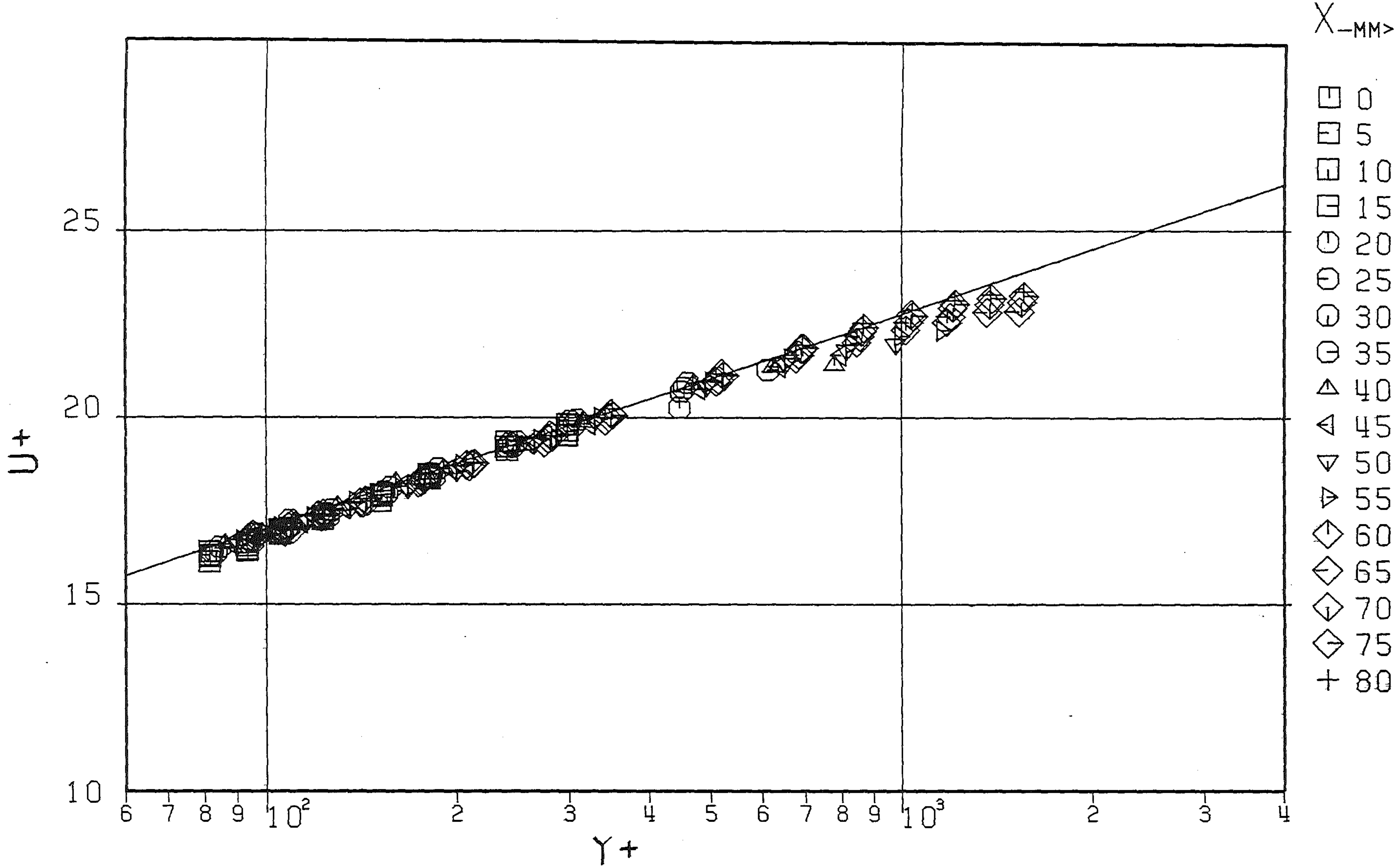


Fig. 7-4 Distribution of dimensionless velocity in the x/y-part of quadrant 4

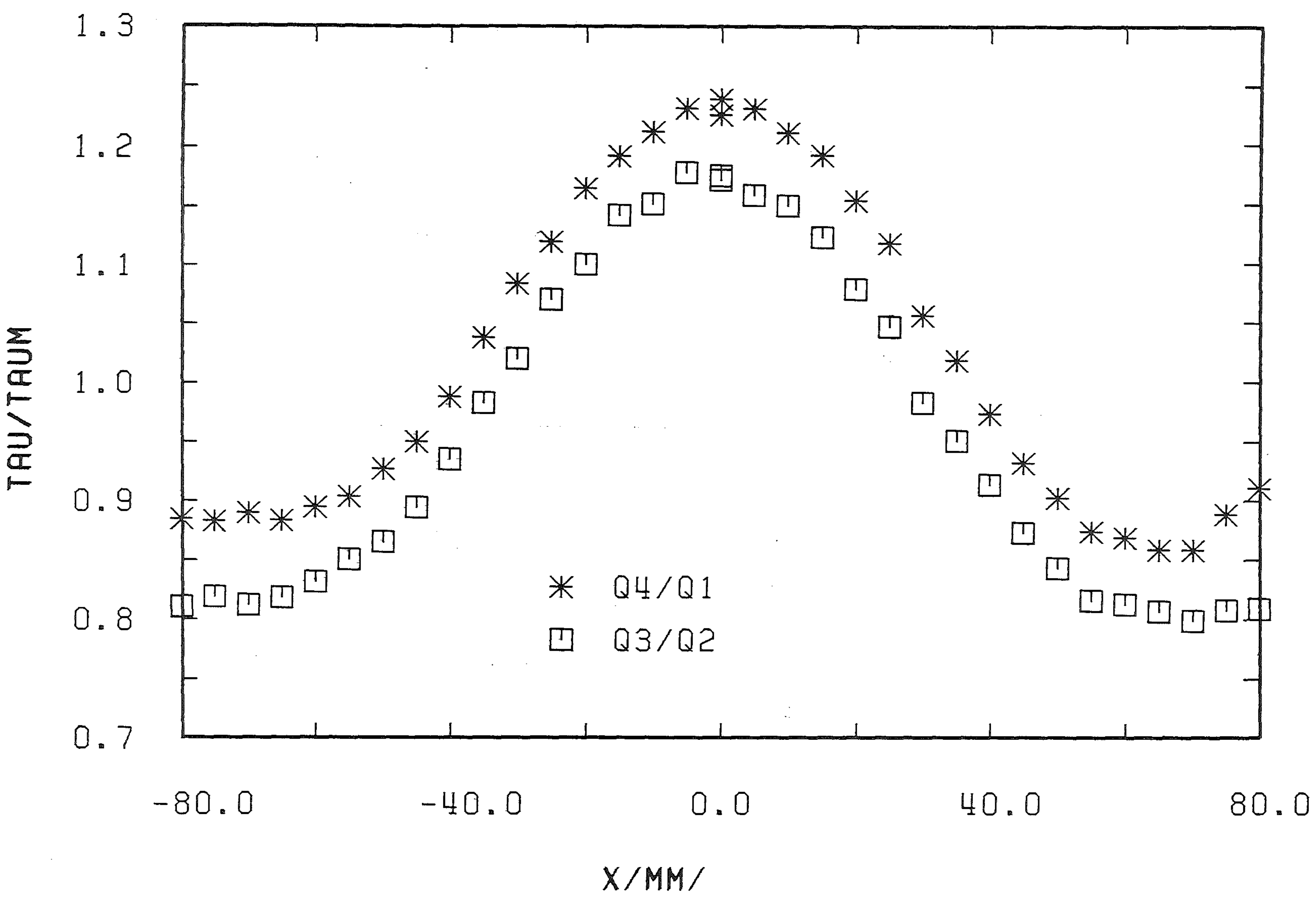


Fig. 8 Distribution of wall shear stress on the channel walls

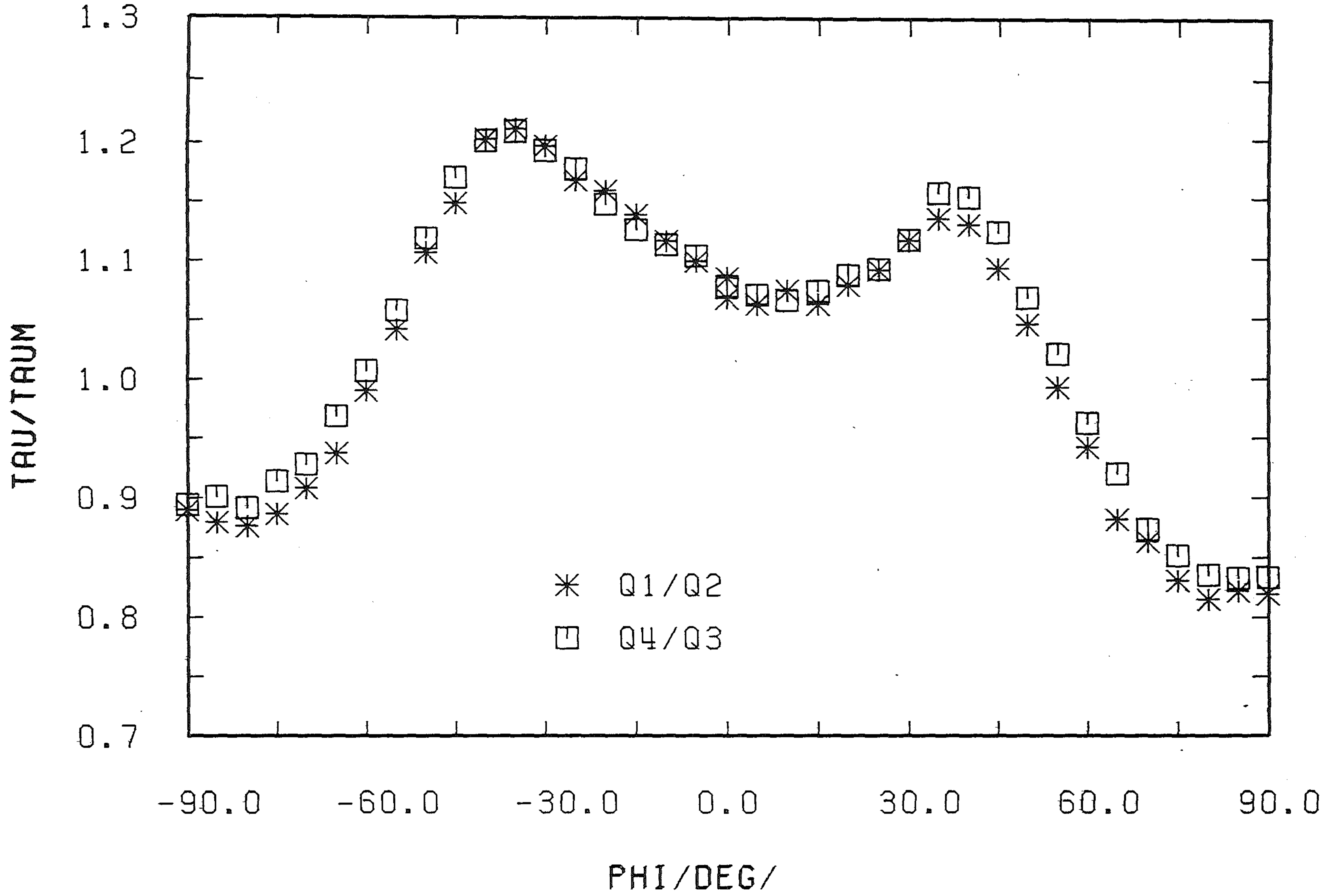


Fig. 9 Distribution of wall shear stress on the rod walls

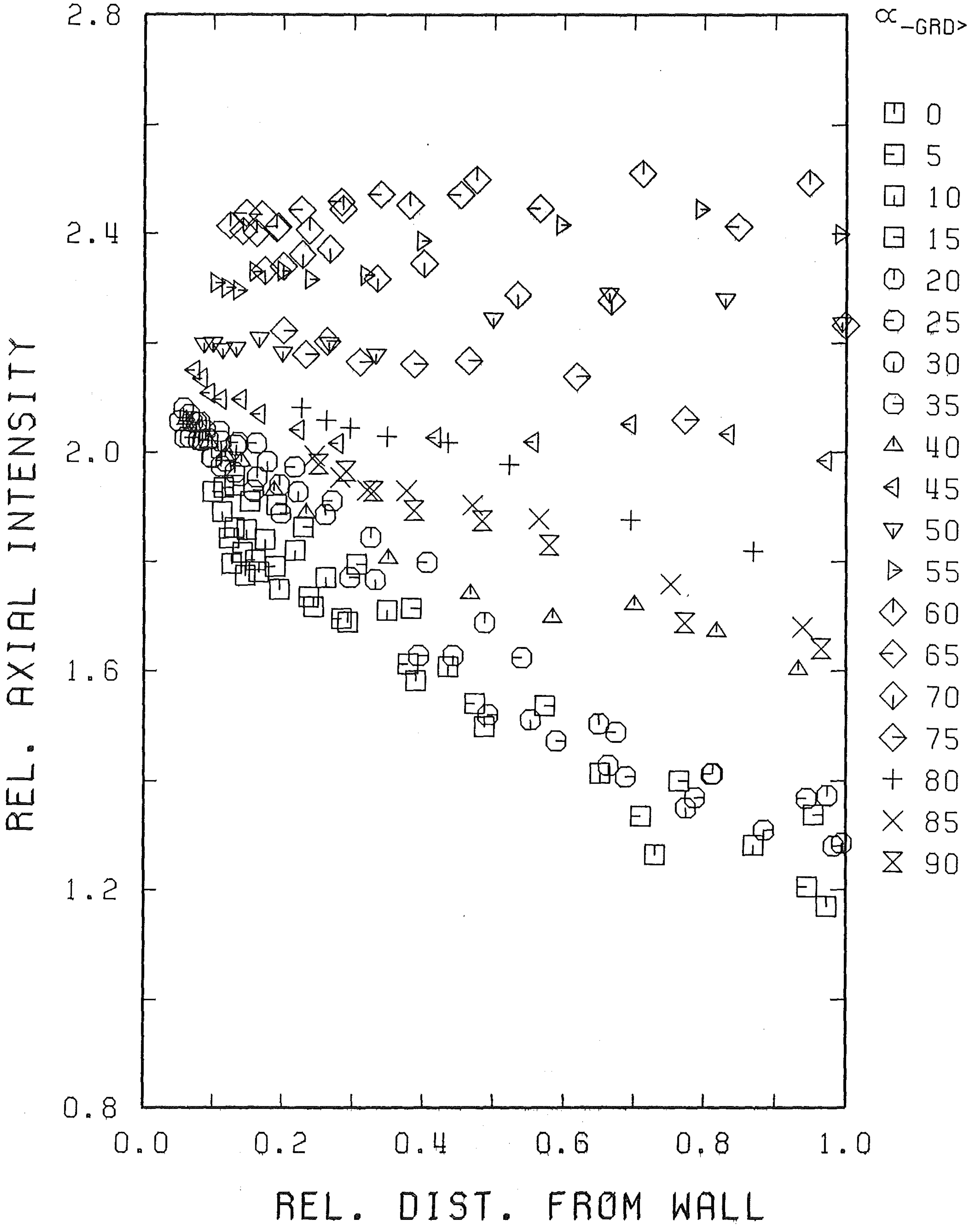


Fig. 10-1 Distribution of axial intensity in the r/ϕ-part of quadrant 1

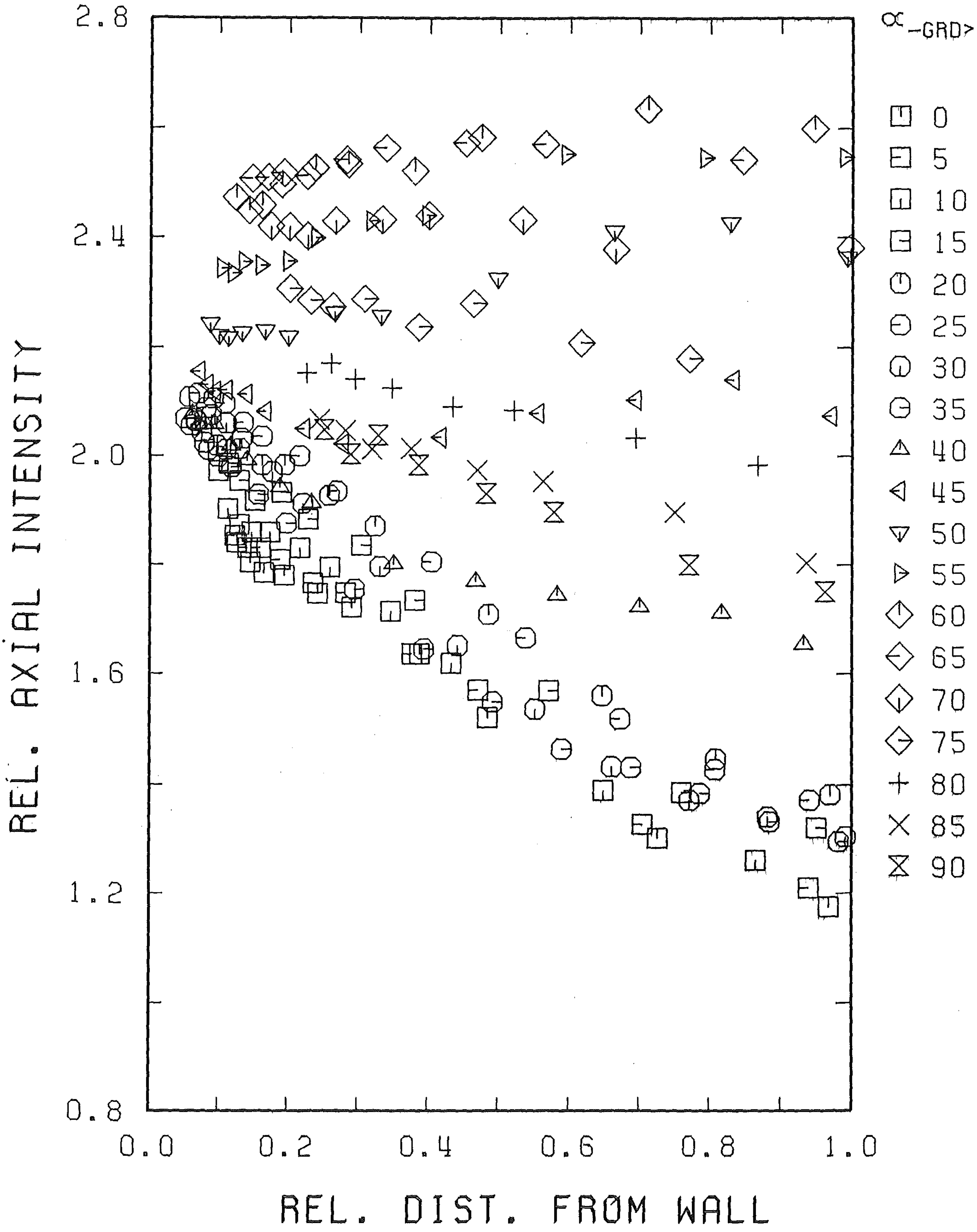


Fig. 10-2 Distribution of axial intensity in the r/ϕ-part
of quadrant 2

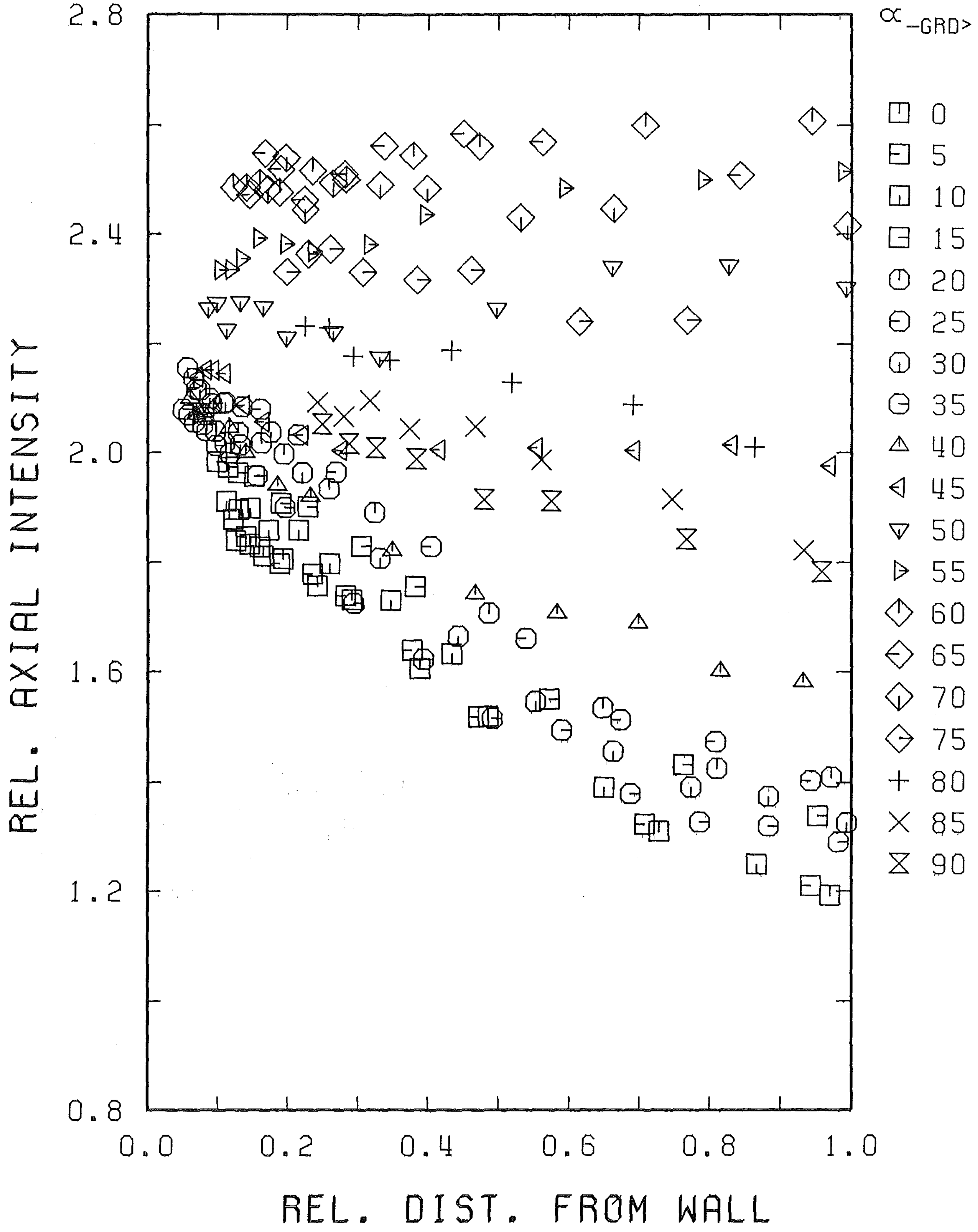


Fig. 10-3 Distribution of axial intensity in the r/ϕ-part of quadrant 3 .

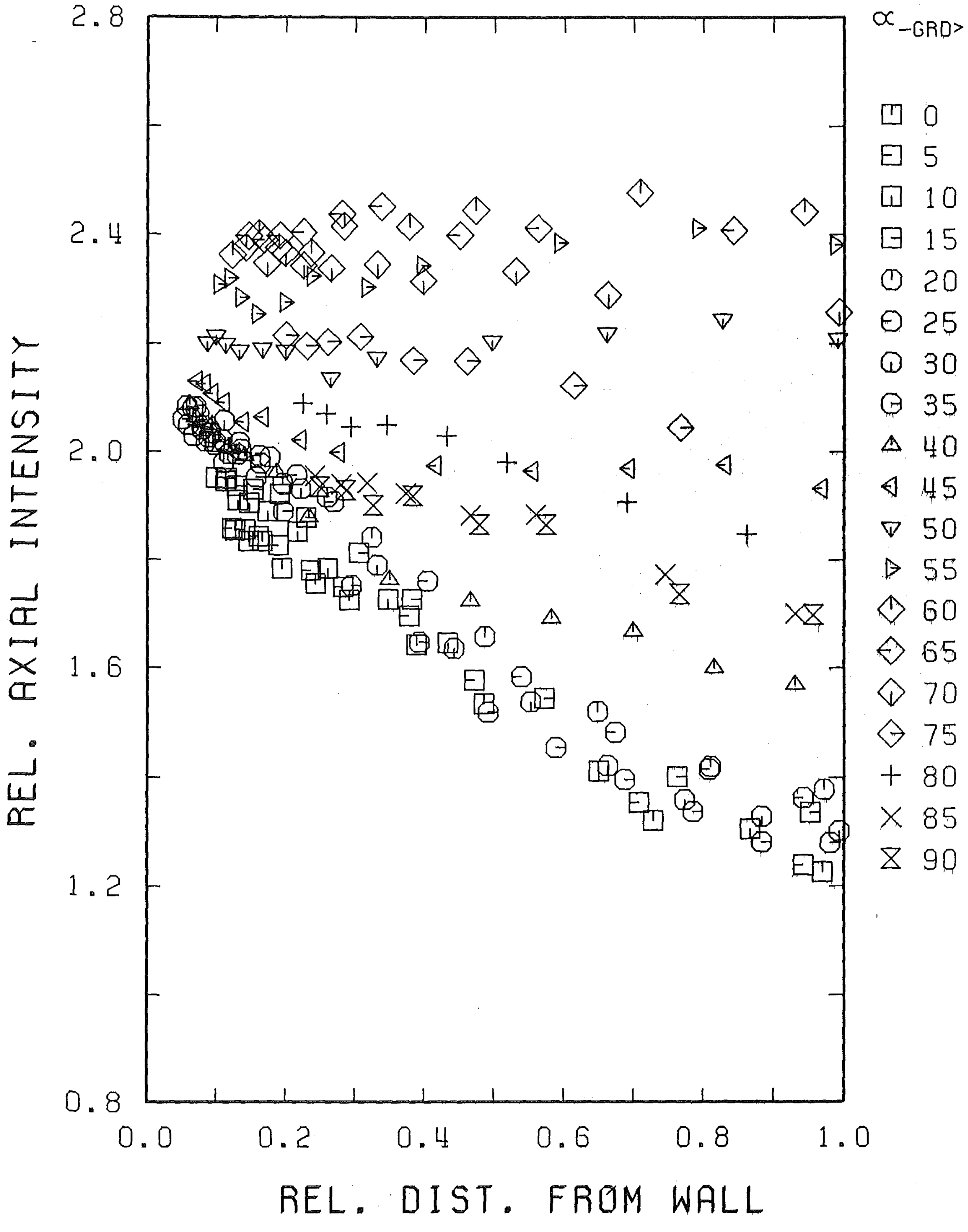


Fig. 10-4 Distribution of axial intensity in the r/ϕ-part of quadrant 4

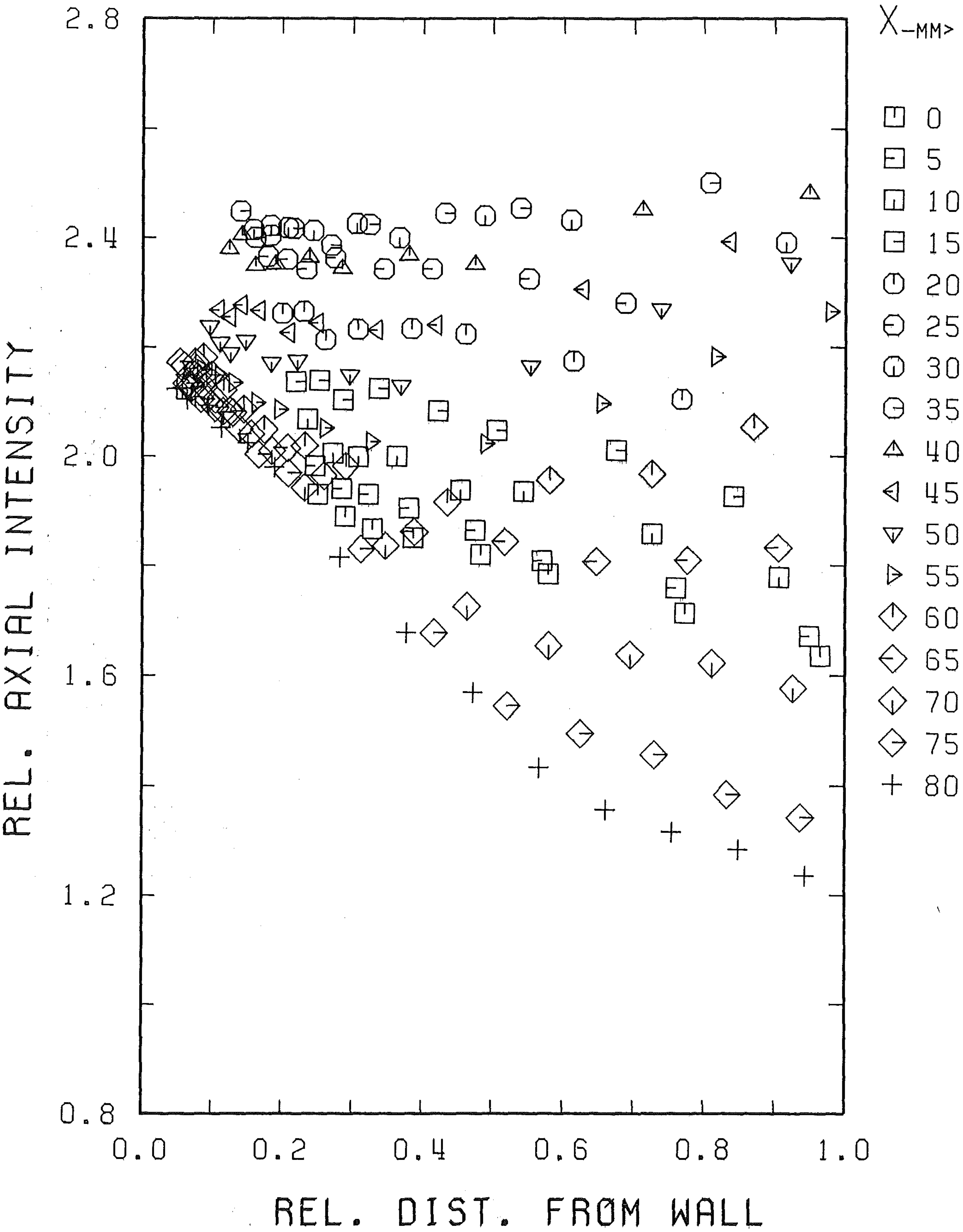


Fig. 11-1 Distribution of axial intensity in the x/y-part of quadrant 1

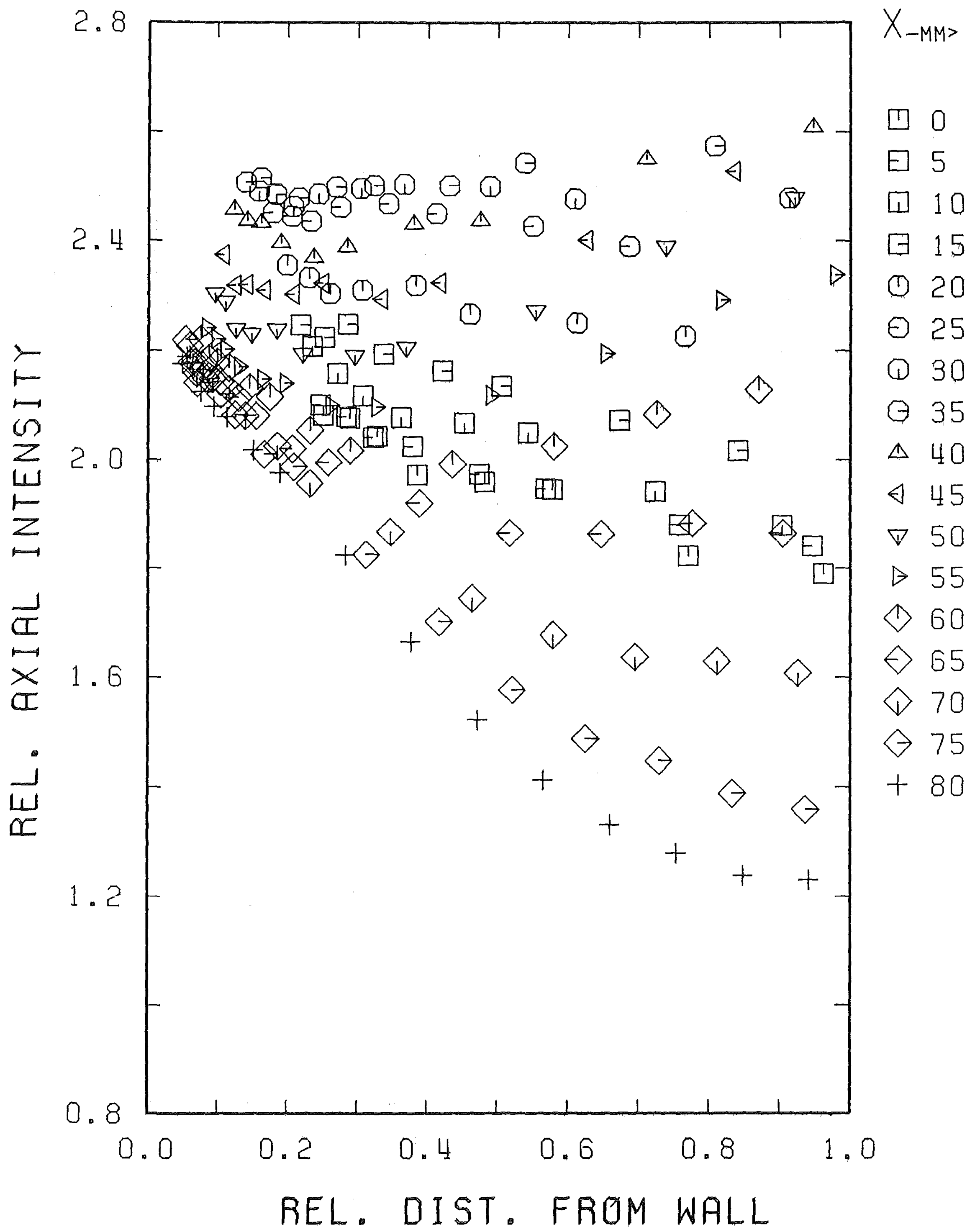


Fig. 11-2 Distribution of axial intensity in the x/y-part of quadrant 2

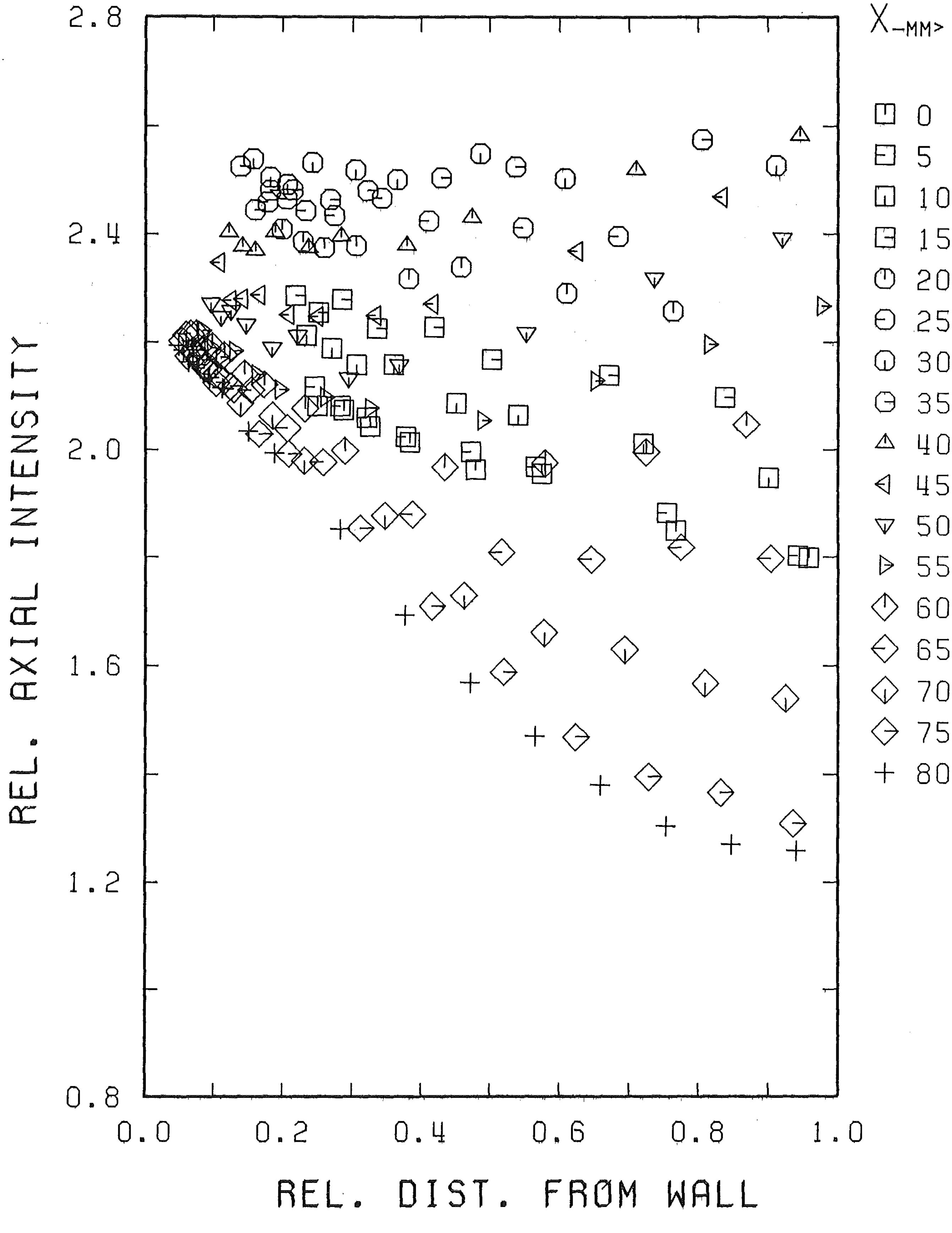


Fig. 11-3 Distribution of axial intensity in the x/y-part of quadrant 3

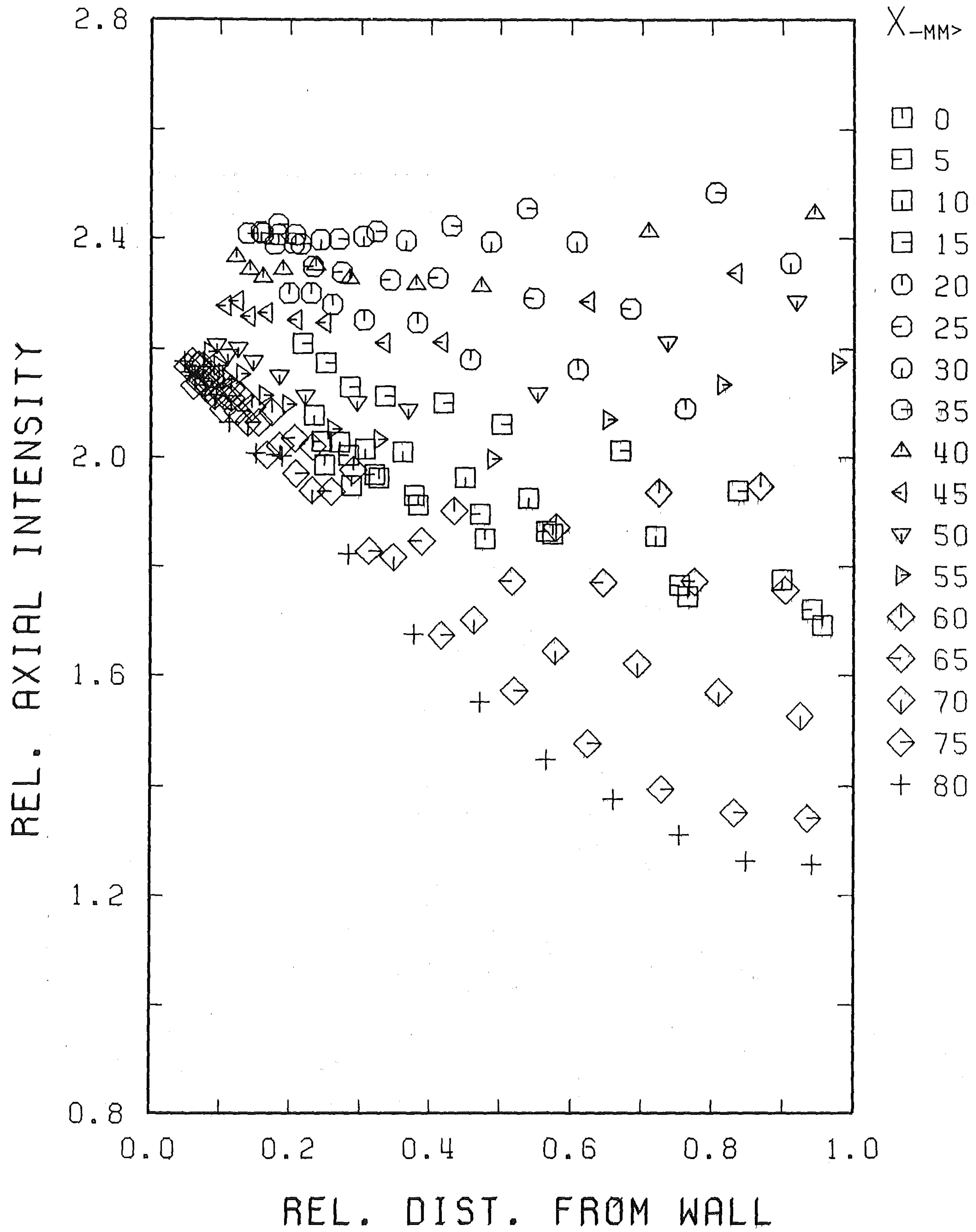


Fig. 11-4 Distribution of axial intensity in the x/y-part of quadrant 4

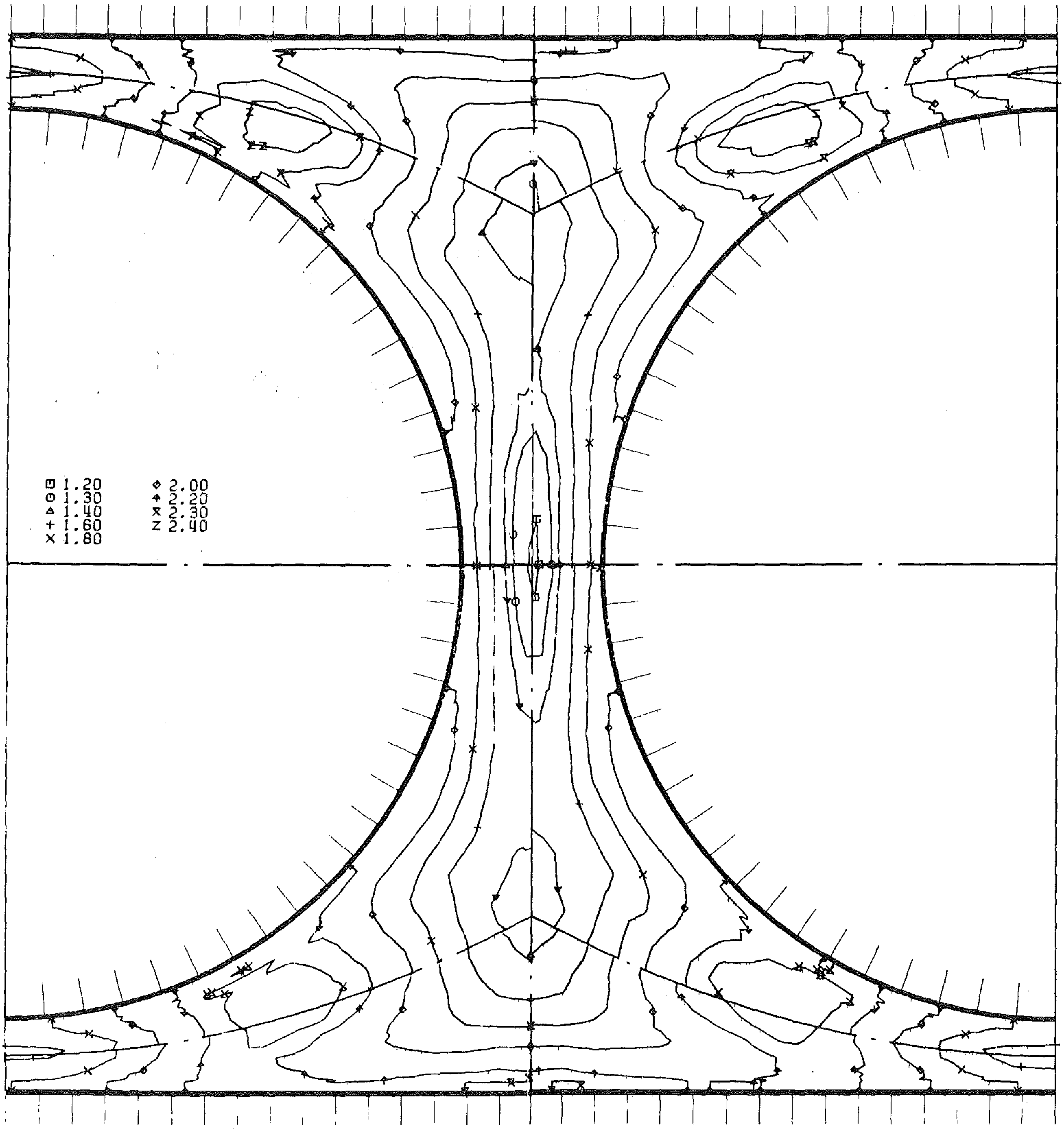


Fig. 12 Contours of axial intensity in the four quadrants

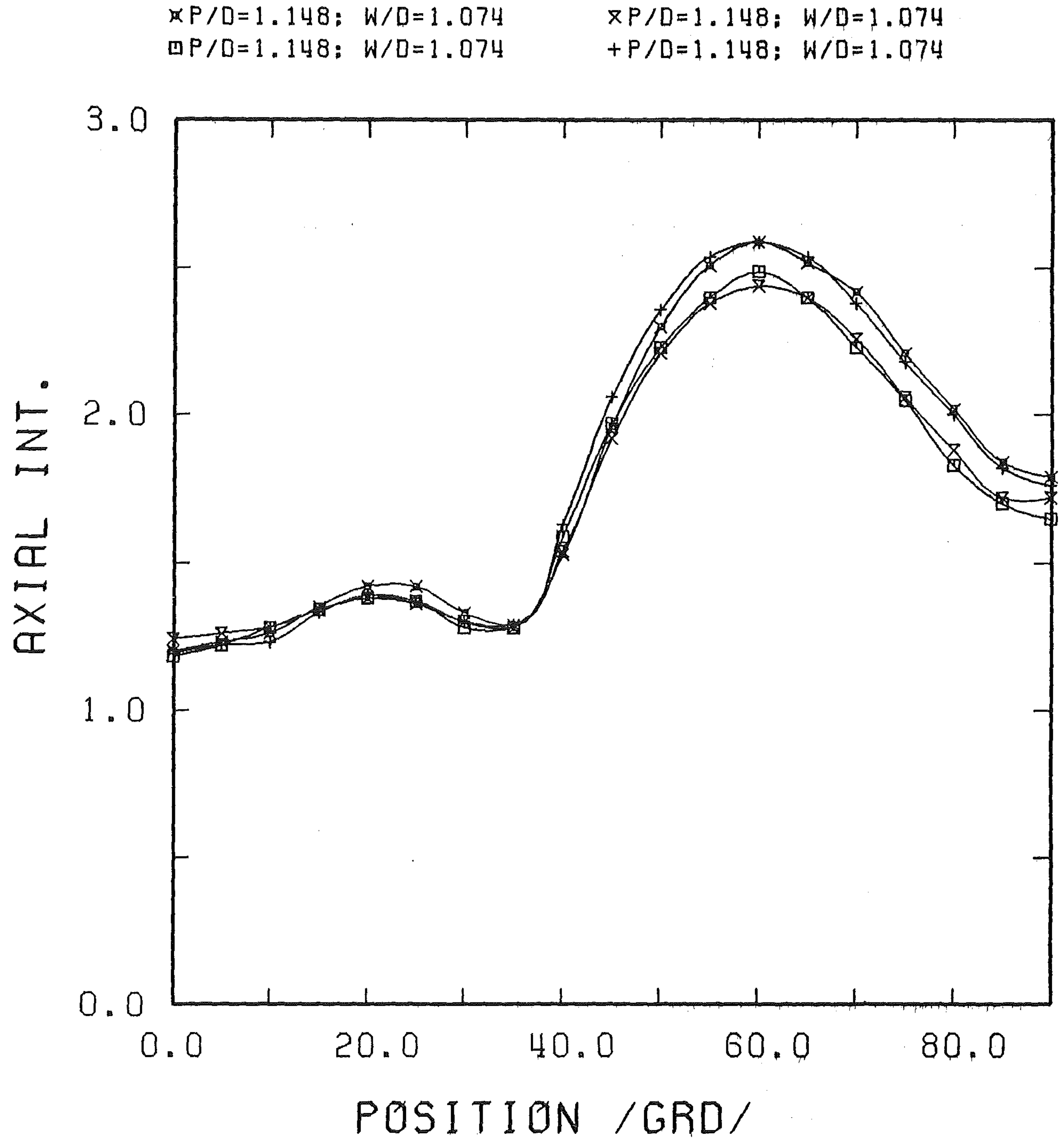


Fig. 12 a) Distribution of axial intensity along the lines of maximum distance from the wall

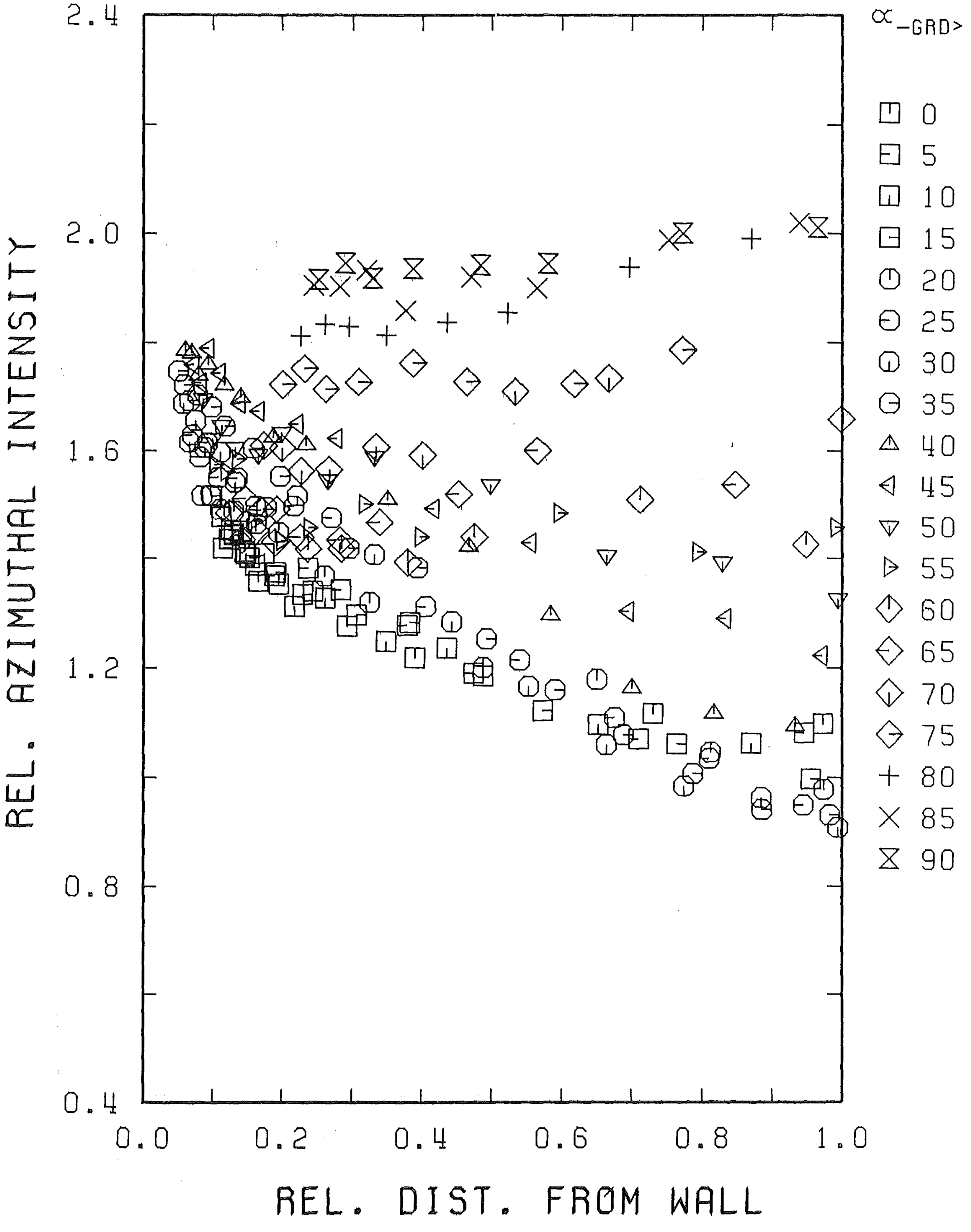


Fig. 13-1 Distribution of azimuthal intensity in the r/ϕ-part of quadrant 1

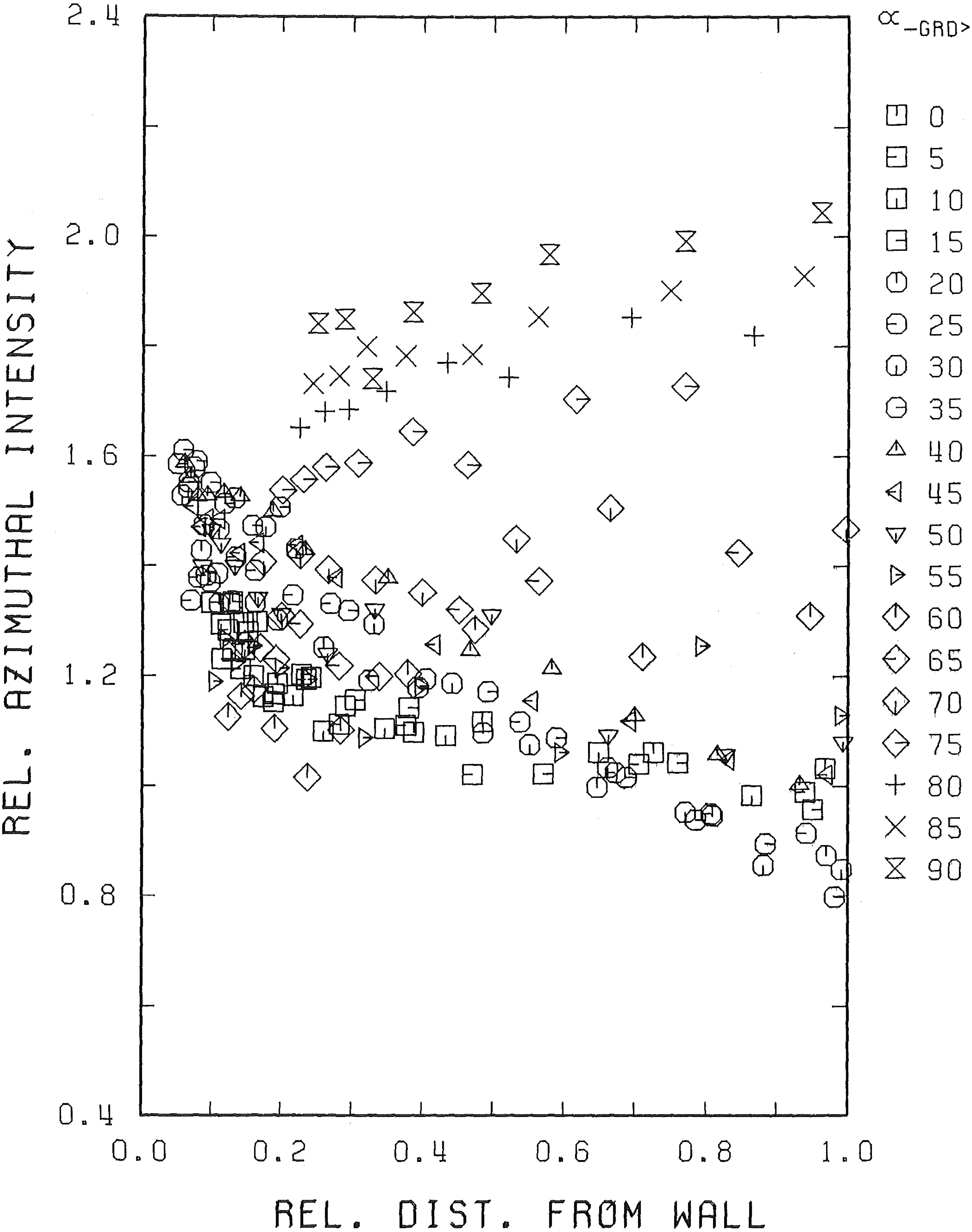


Fig. 13-2 Distribution of azimuthal intensity in the r/ϕ-part of quadrant 2

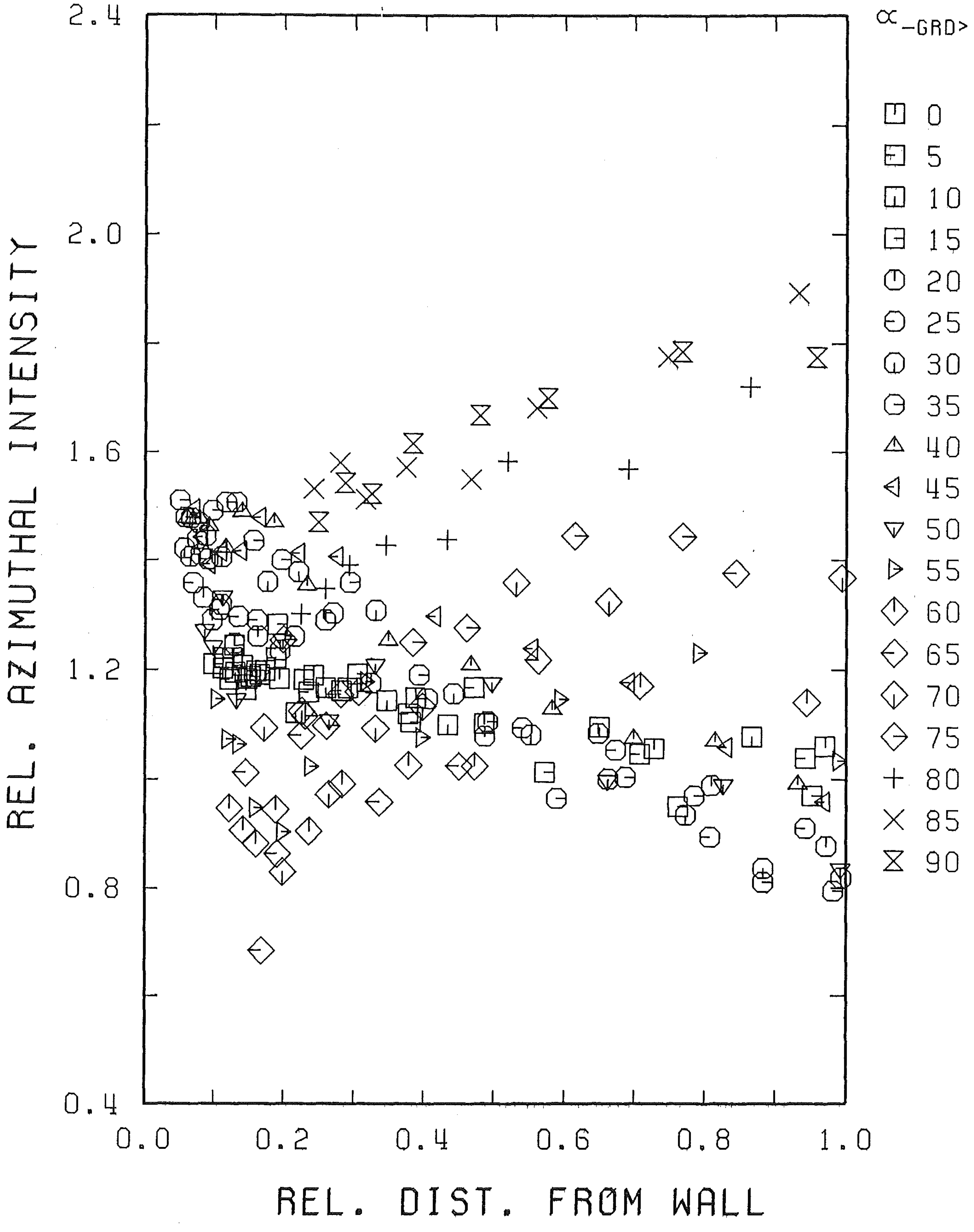


Fig. 13-3 Distribution of azimuthal intensity in the r/ϕ-part of quadrant 3

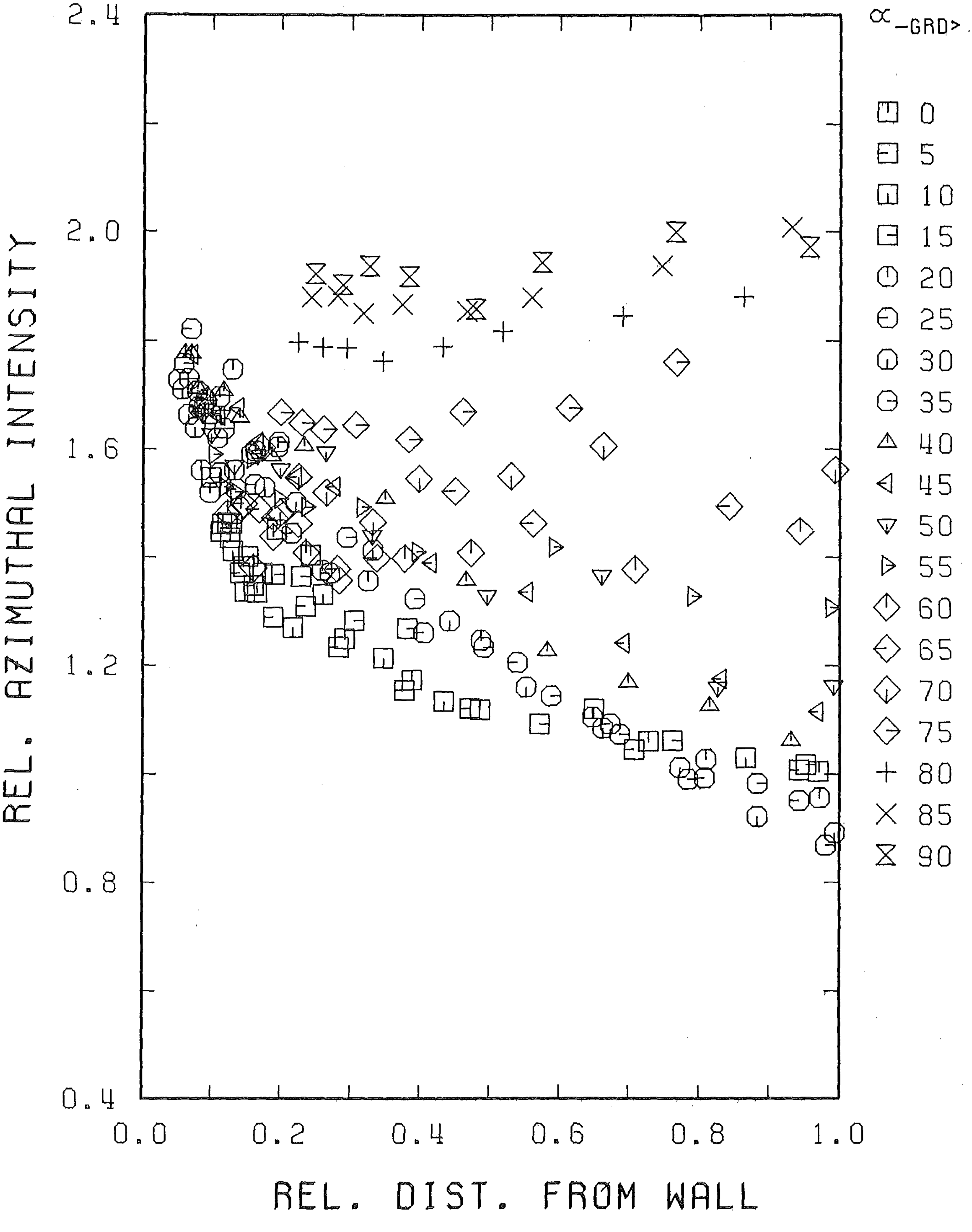


Fig. 13-4 Distribution of azimuthal intensity in the r/ϕ-part of quadrant 4

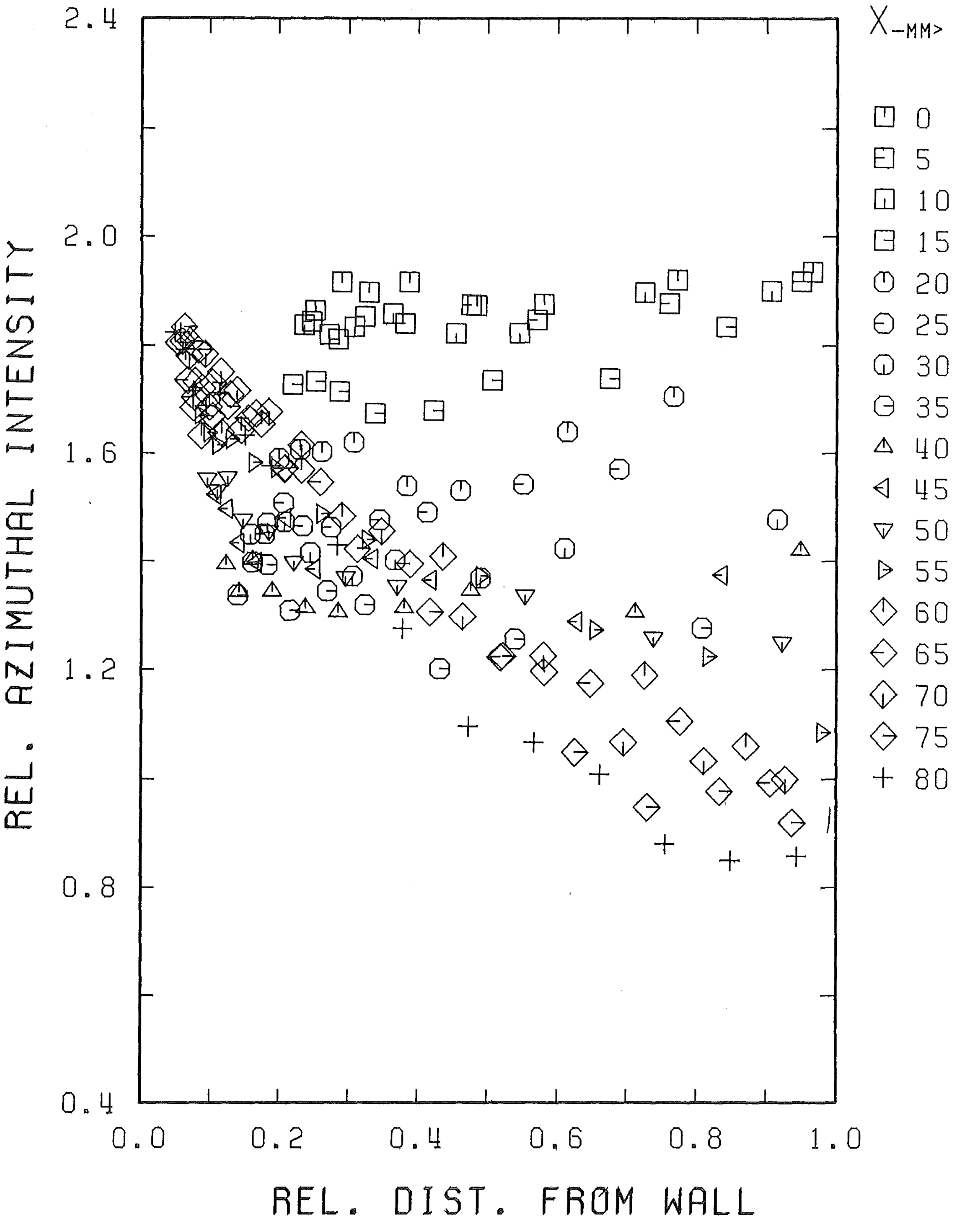


Fig. 14-1 Distribution of azimuthal intensity in the x/y-part of quadrant 1

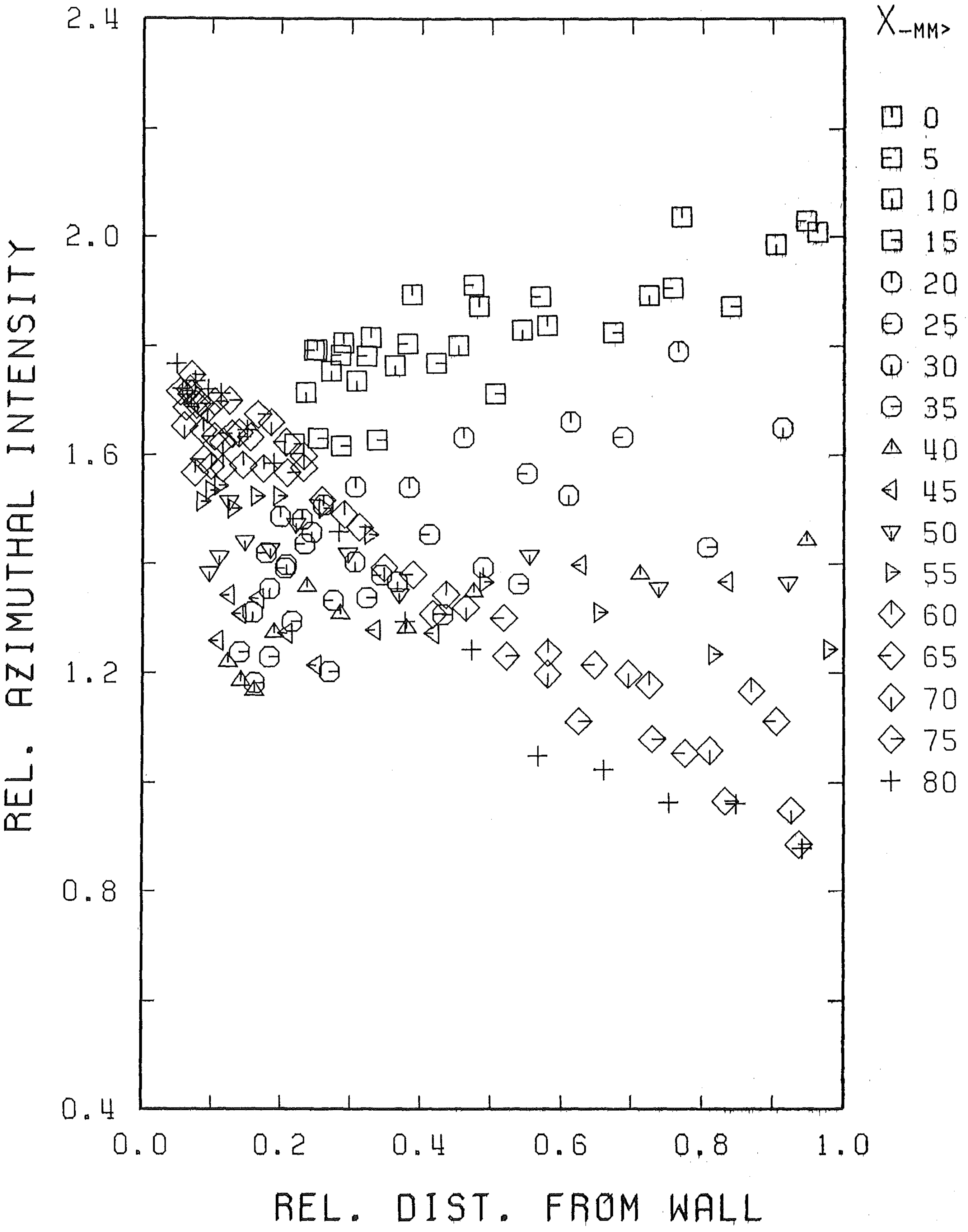


Fig. 14-2 Distribution of azimuthal intensity in the x/y-part of quadrant 2

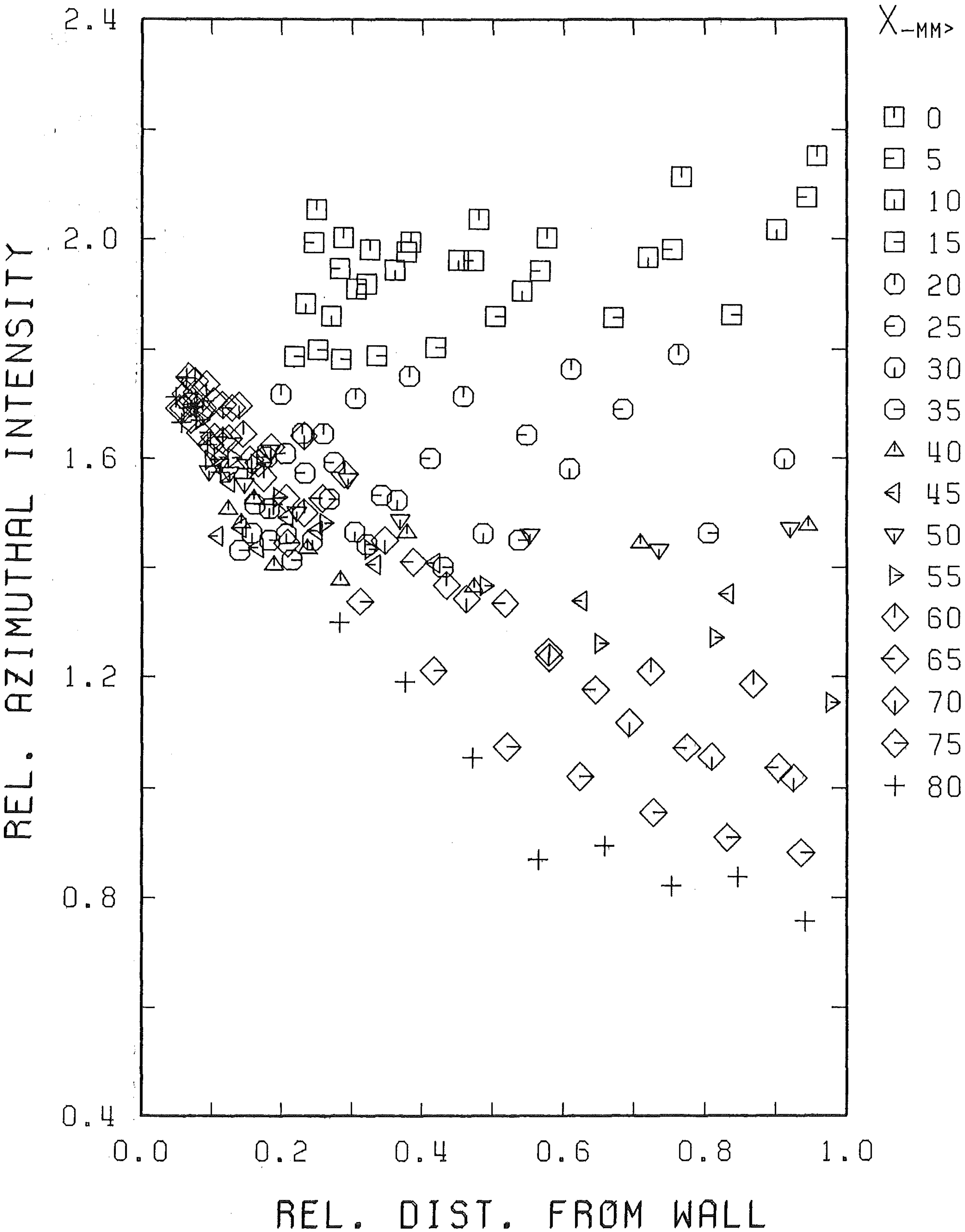


Fig. 14-3 Distribution of azimuthal intensity in the x/y-part of quadrant 3

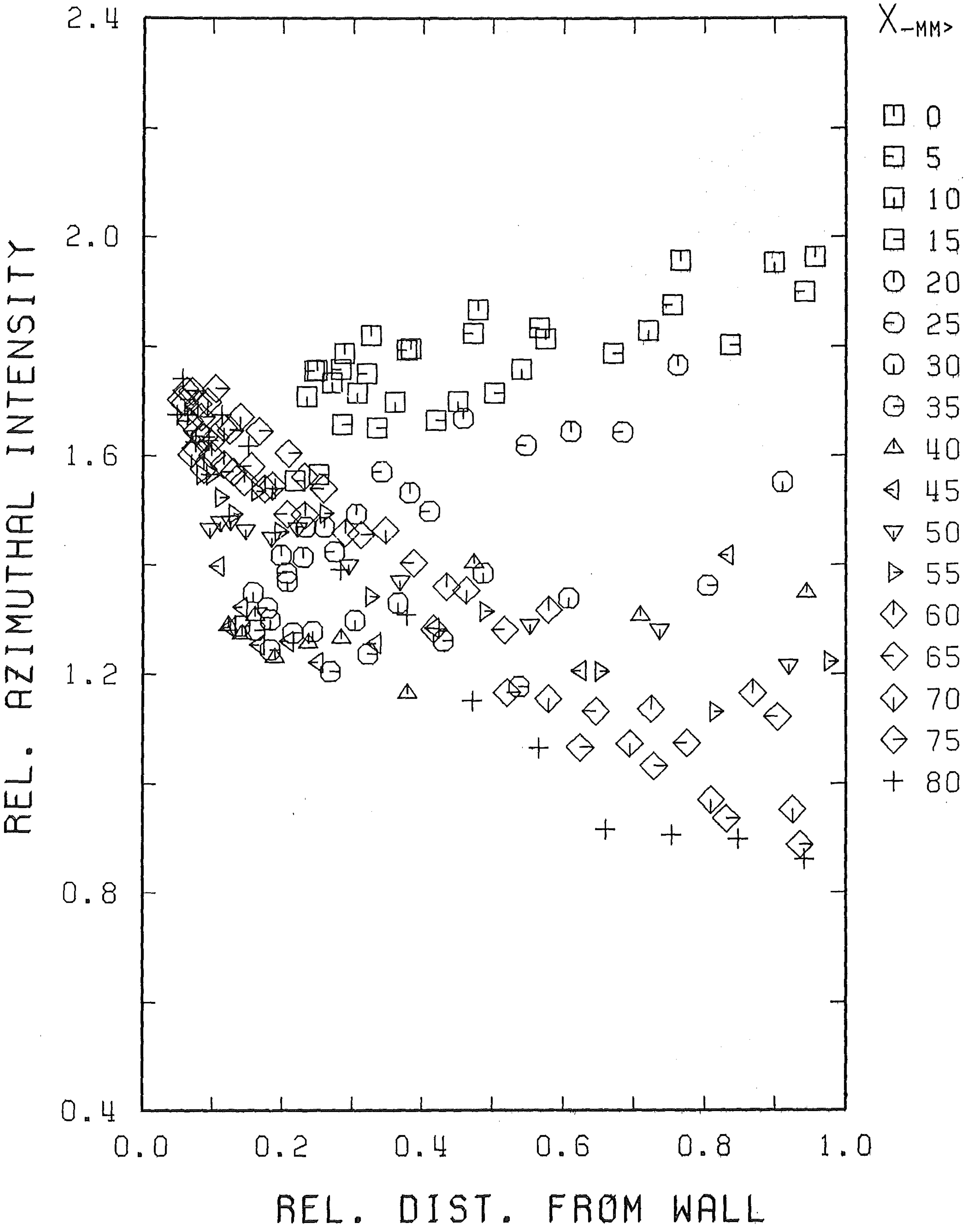


Fig. 14-4 Distribution of azimuthal intensity in the x/y-part of quadrant 4

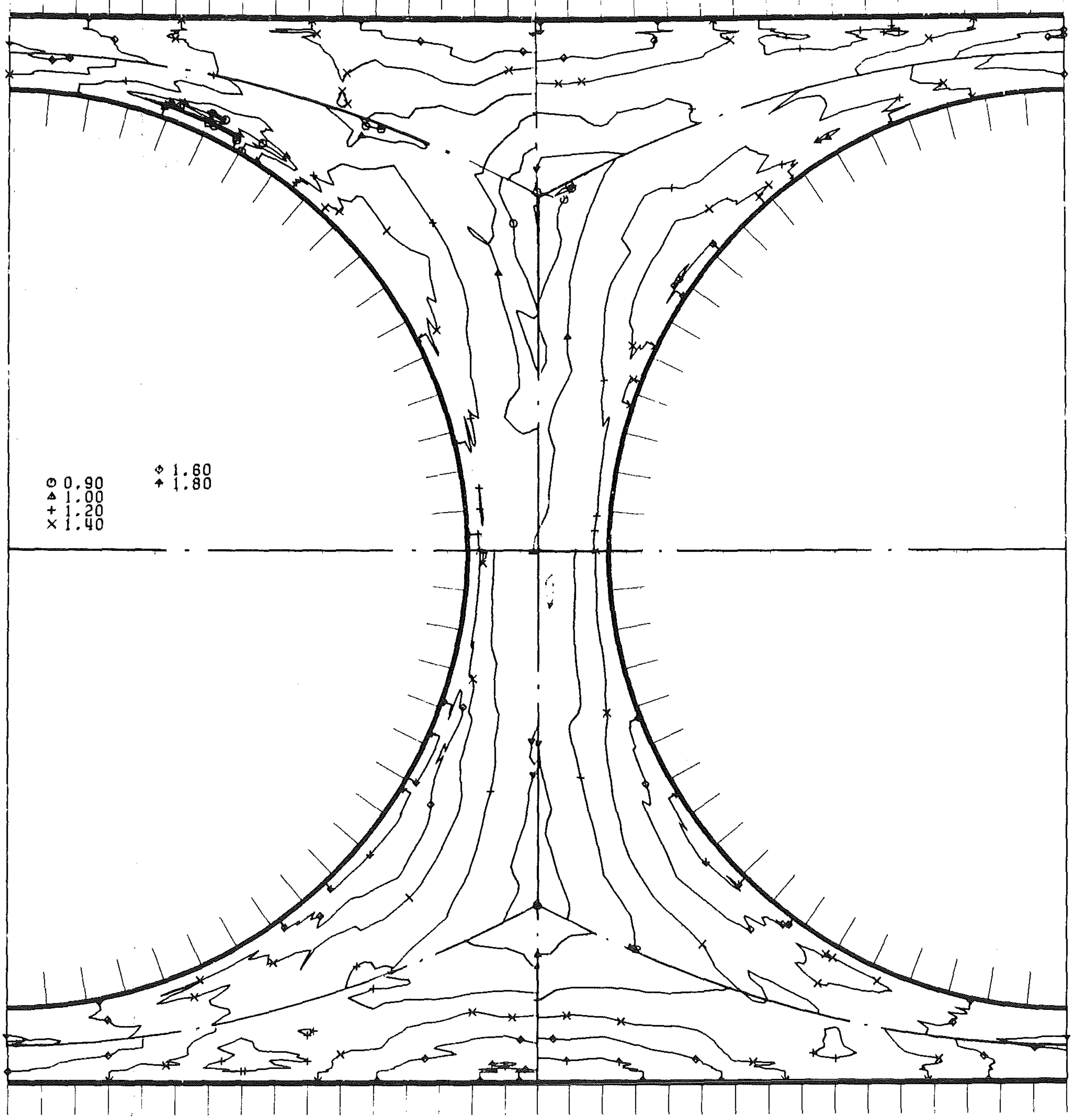


Fig. 15 Contorus of azimuthal intensity in the four quadrants

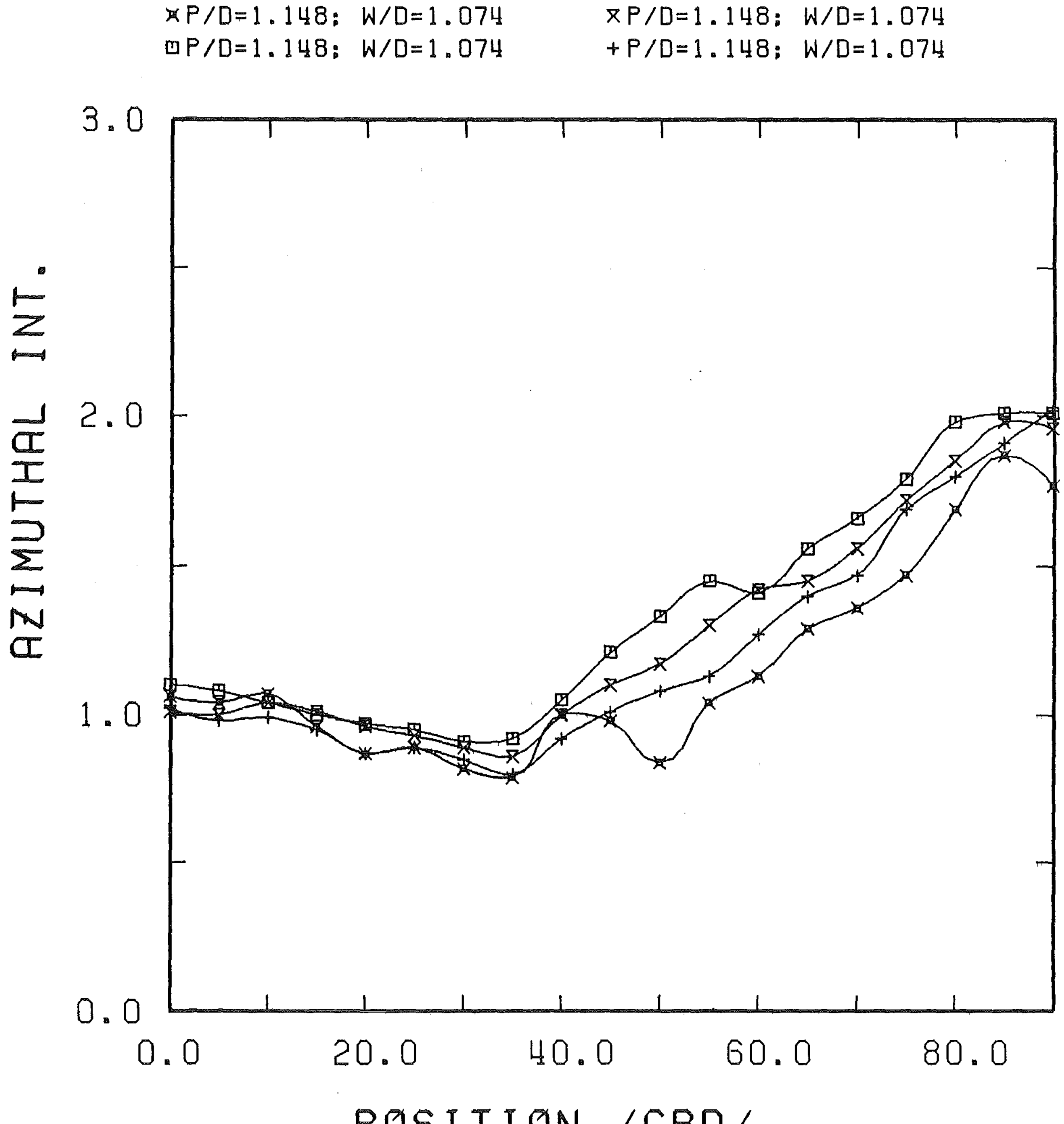


Fig. 15 a) Distribution of azimuthal intensity along the lines of maximum distance from the wall

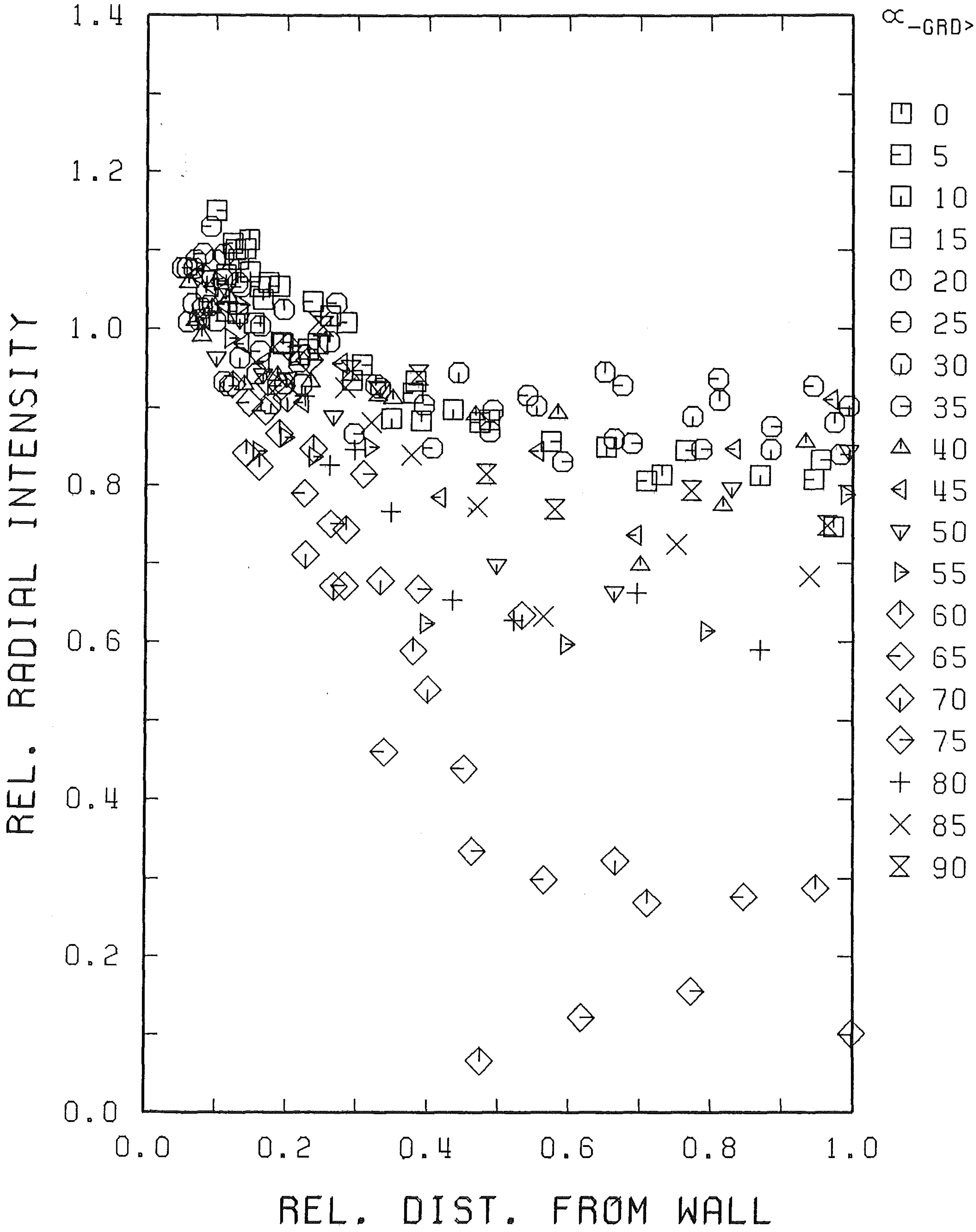


Fig. 16-1 Distribution of radial intensity in the r/ϕ-part of quadrant 1

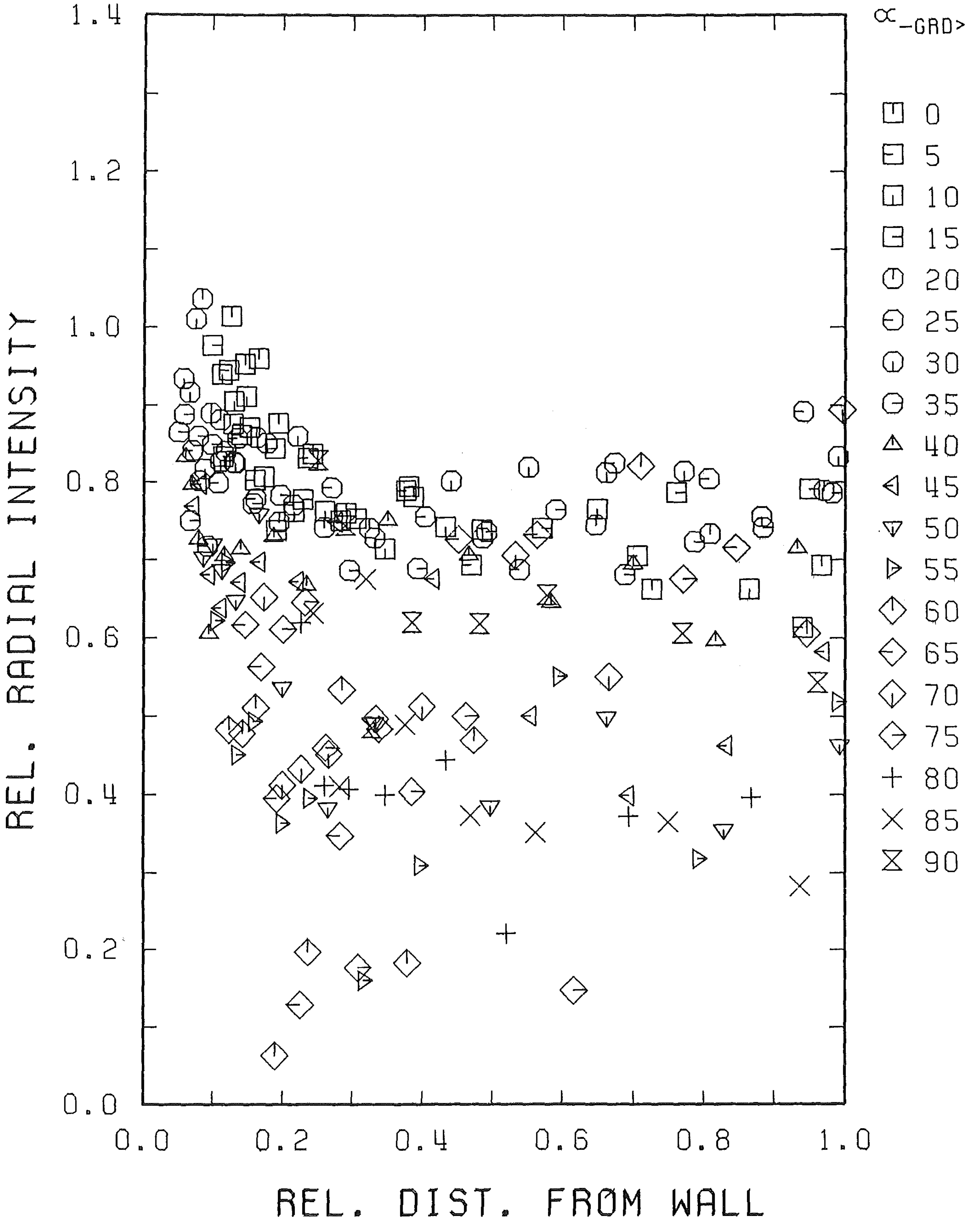


Fig. 16-2 Distribution of radial intensity in the r/ϕ-part of quadrant 2 .

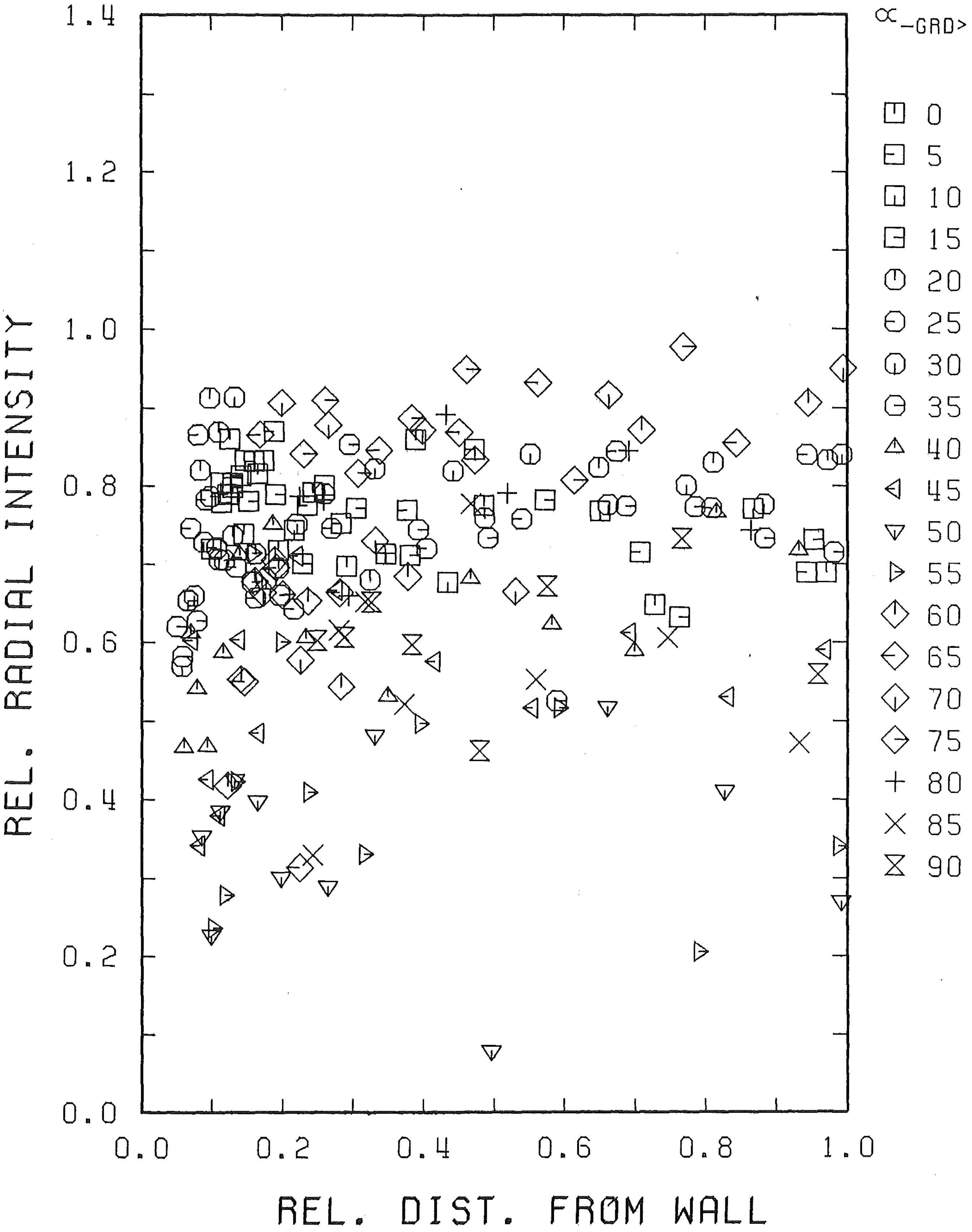


Fig. 16-3 Distribution of radial intensity in the r/ϕ-part of quadrant 3

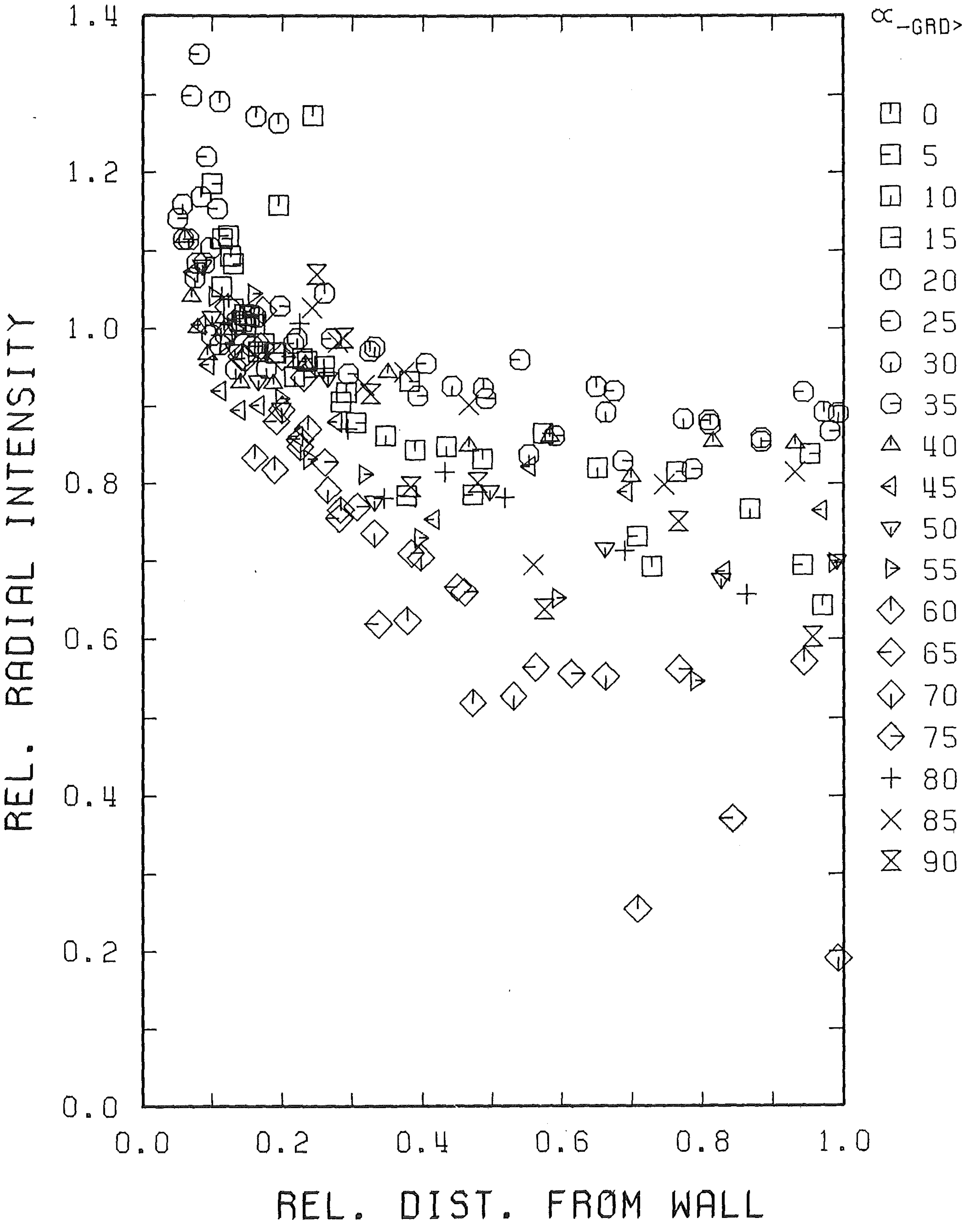


Fig. 16-4 Distribution of radial intensity in the r/ϕ-part of quadrant 4

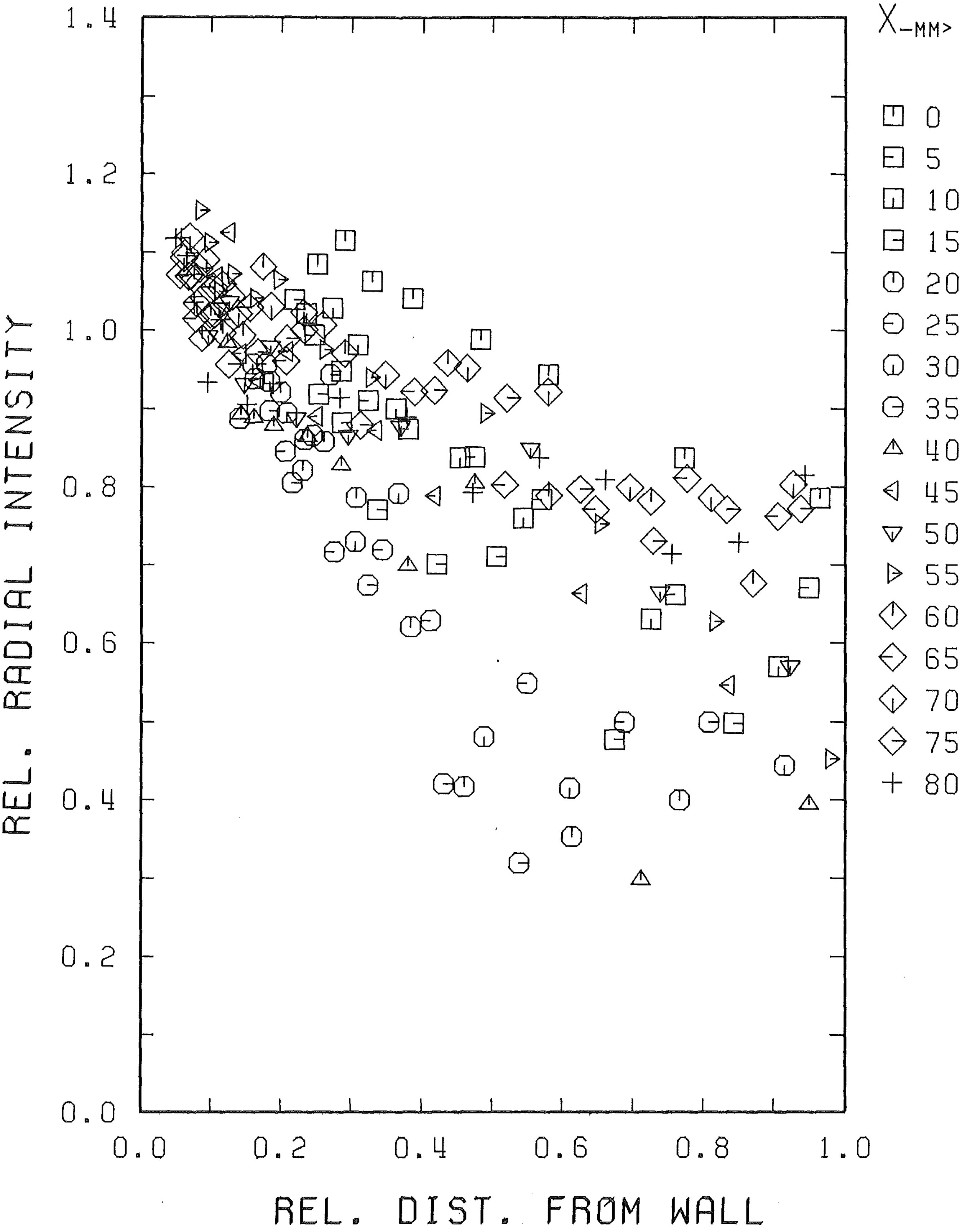


Fig. 17-1 Distribution of radial intensity in the x/y-part of quadrant 1.

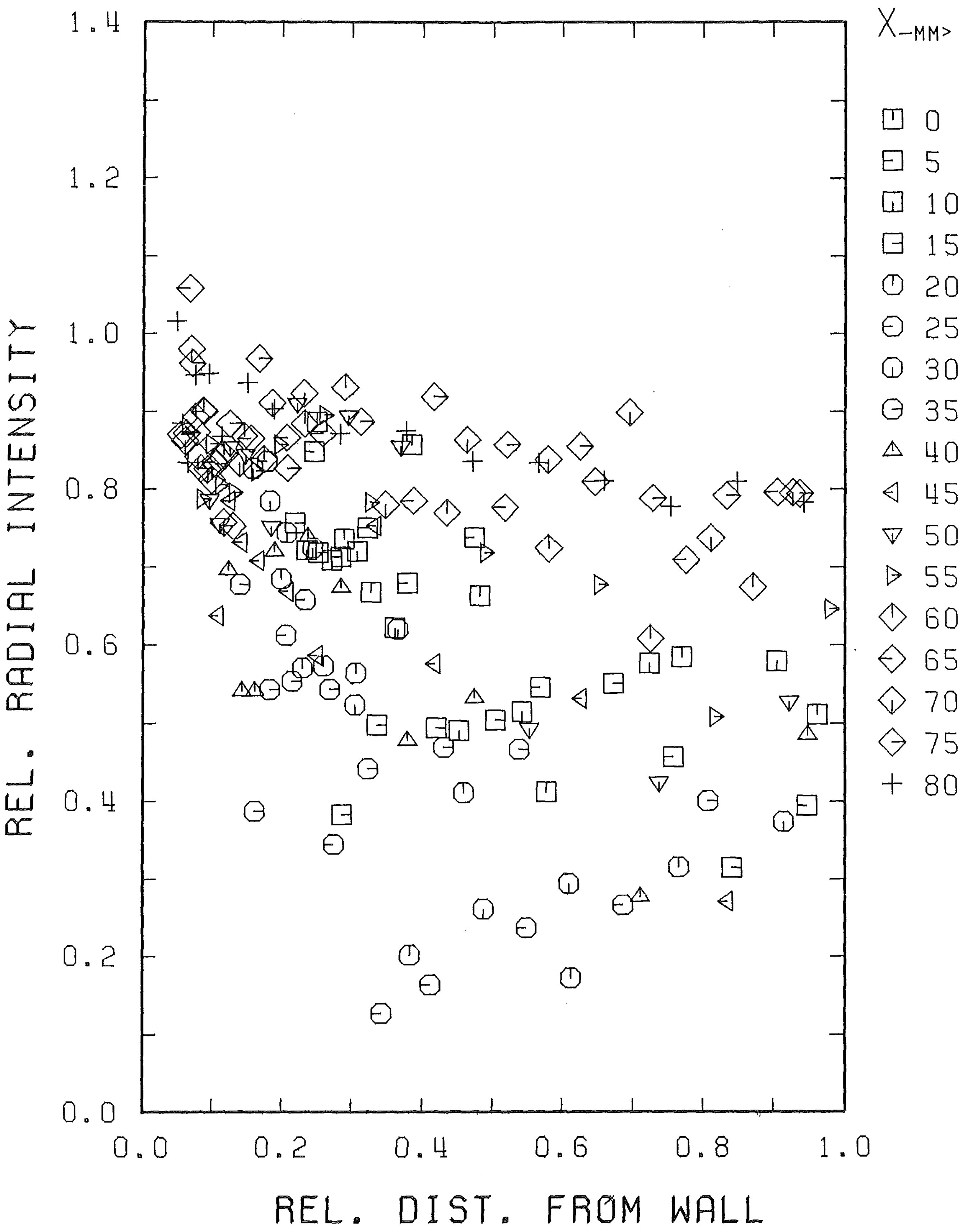


Fig. 17-2 Distribution of radial intensity in the x/y-part of quadrant 2

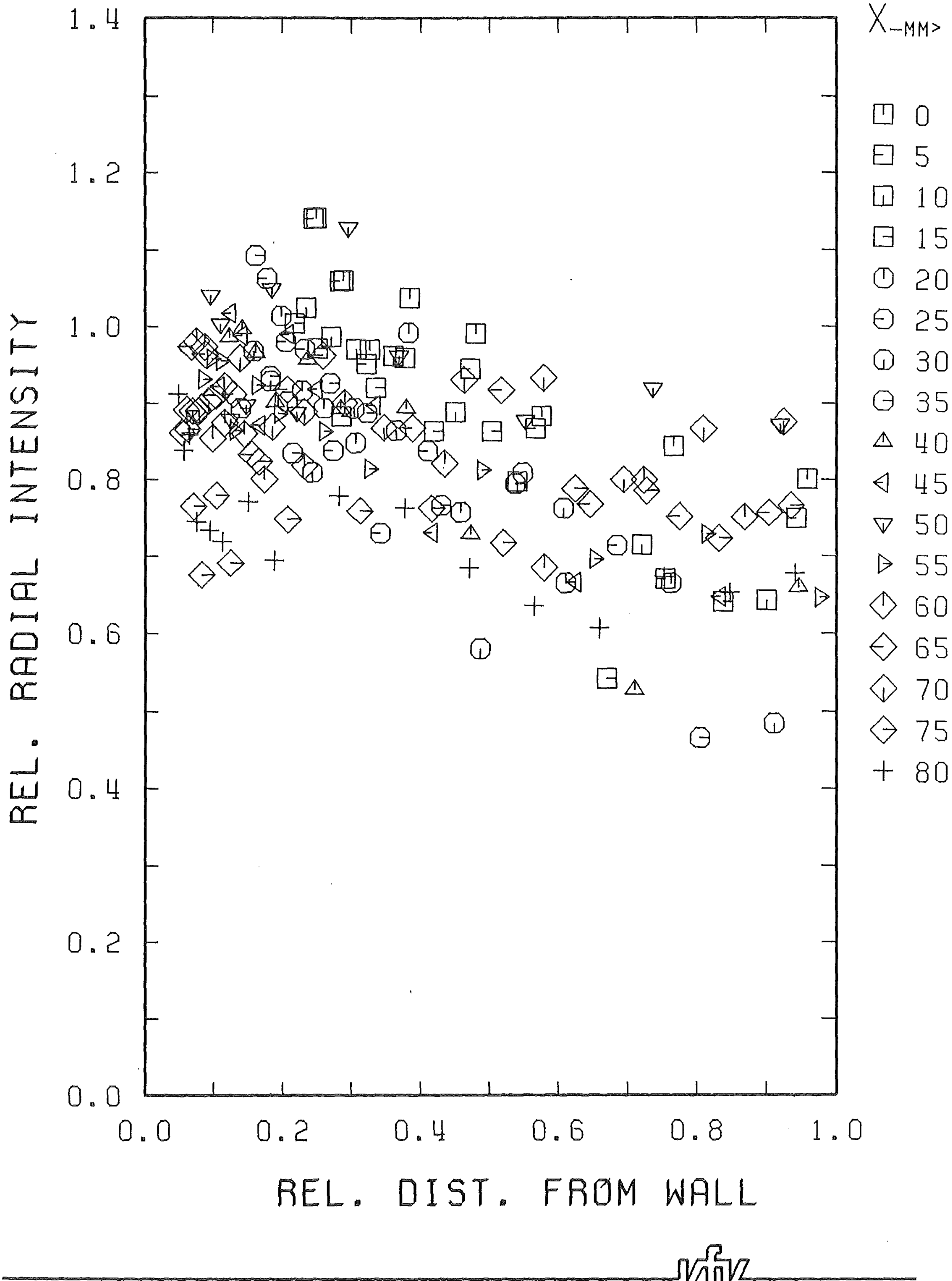


Fig. 17-3 Distribution of radial intensity in the x/y-part of quadrant 3 .

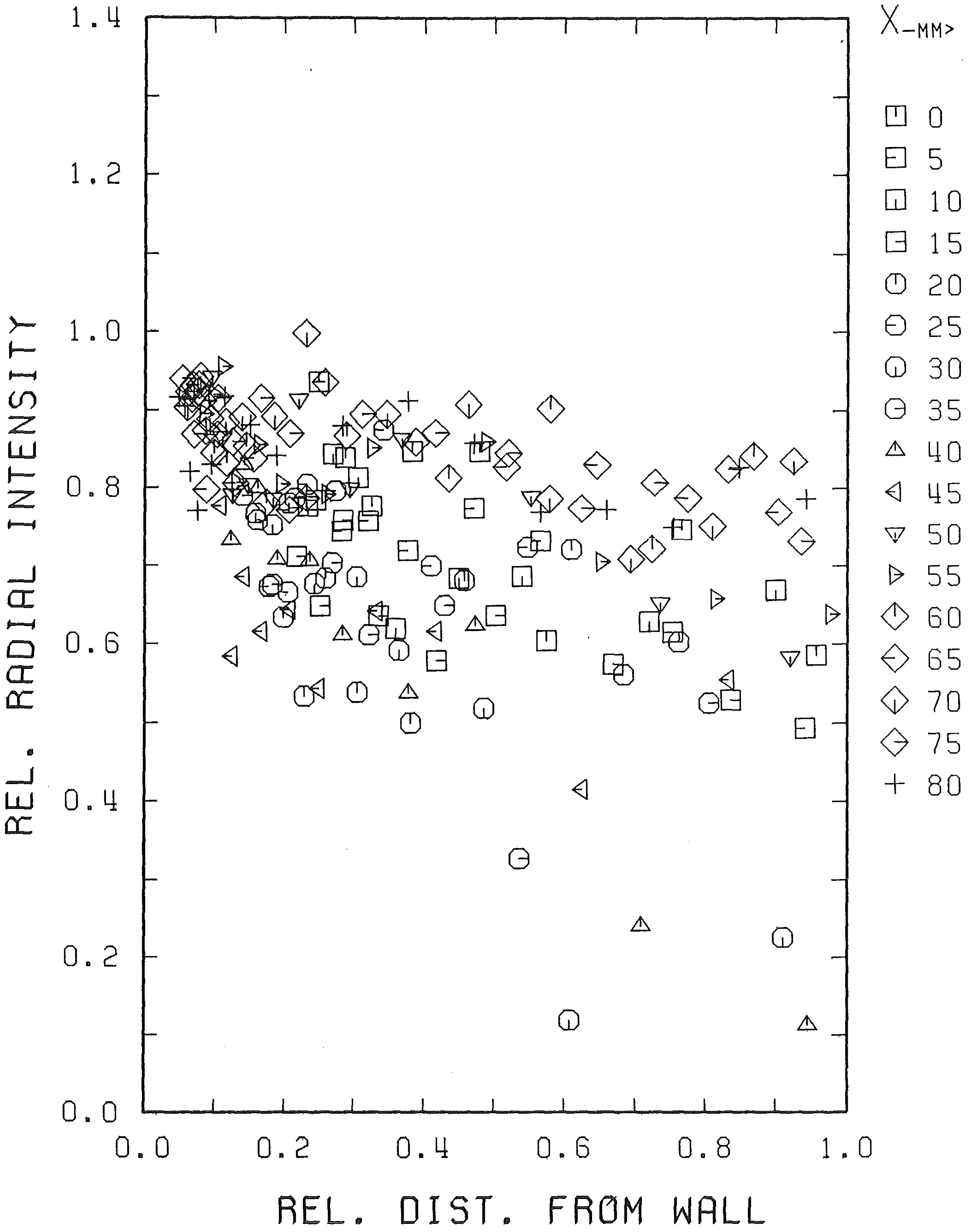


Fig. 17-4 Distribution of radial intensity in the x/y-part of quadrant 4

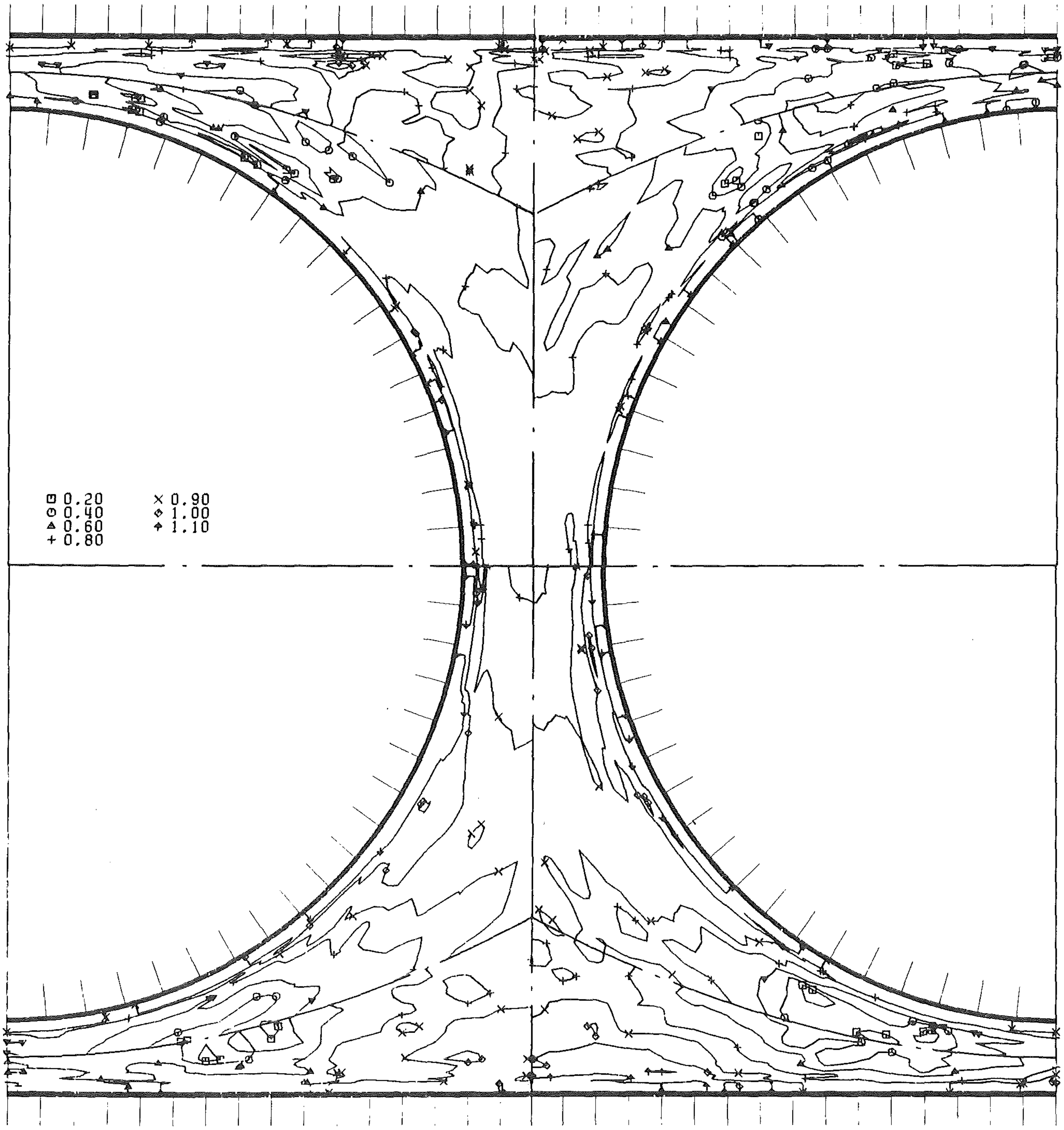


Fig. 18 Contours of radial intensity in the four quadrants

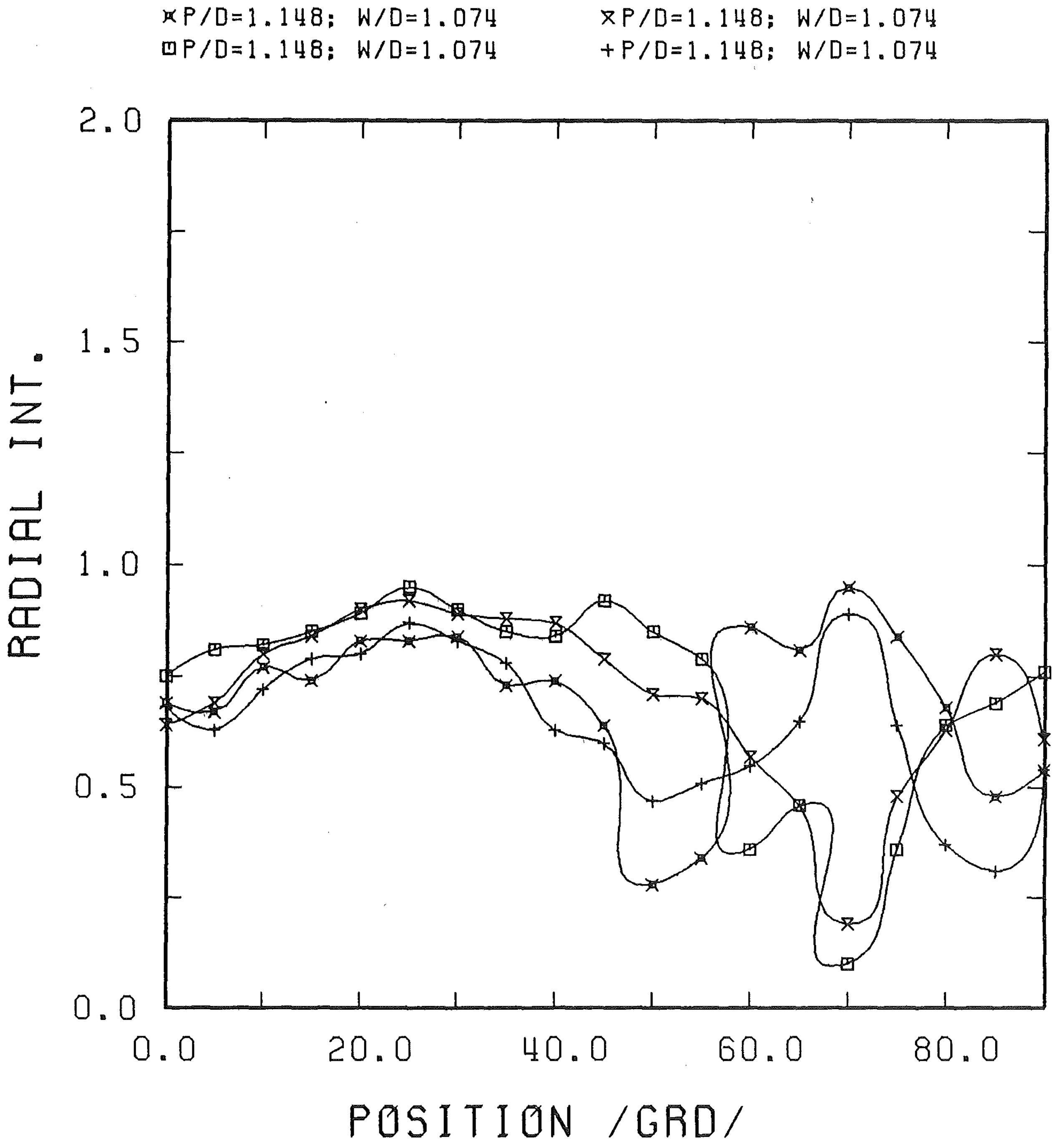


Fig. 18a Distribution of radial intensity along the lines of maximum distance from the wall

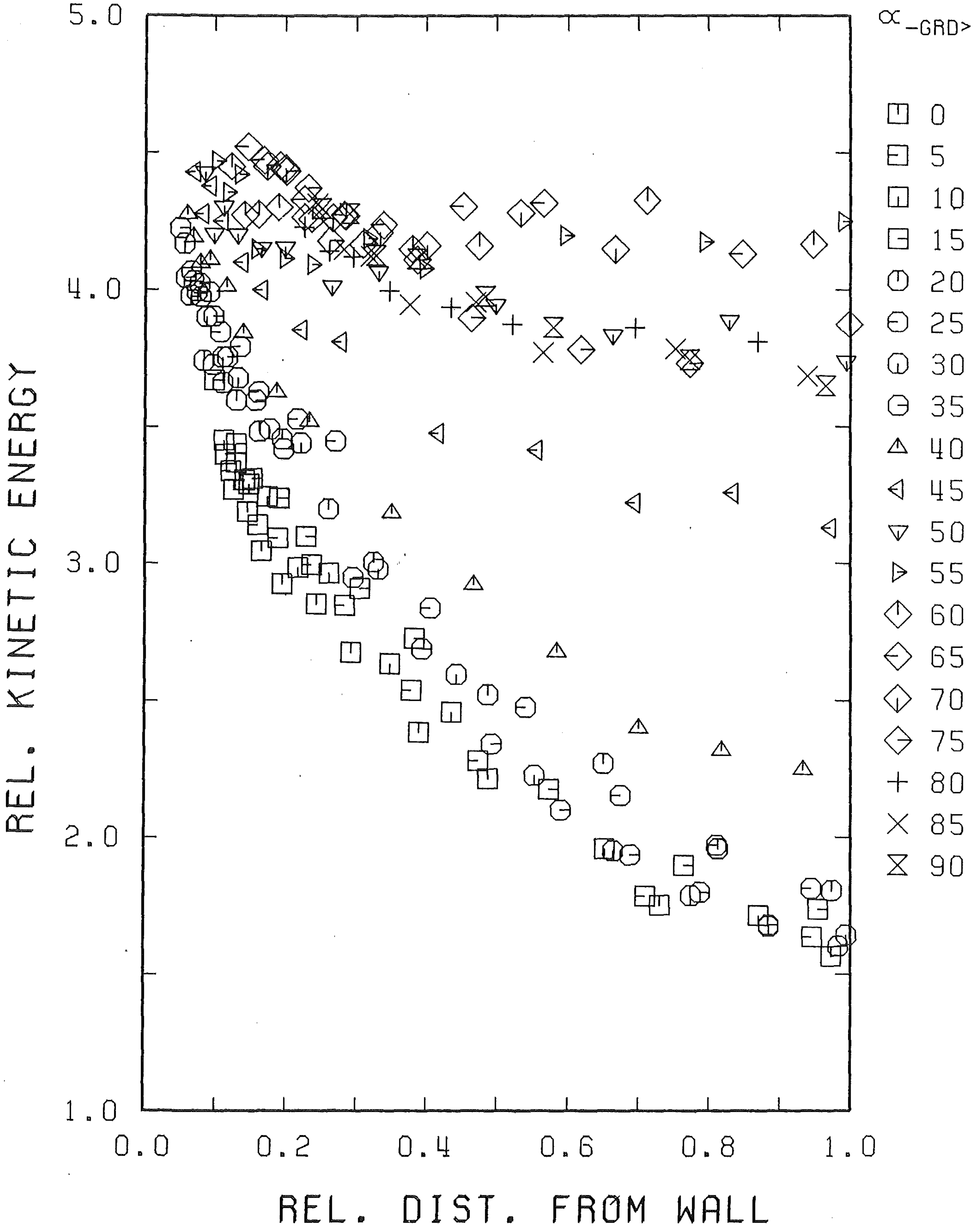


Fig. 19-1 Distribution of kinetic energy in the r/ϕ-part of quadrant 1

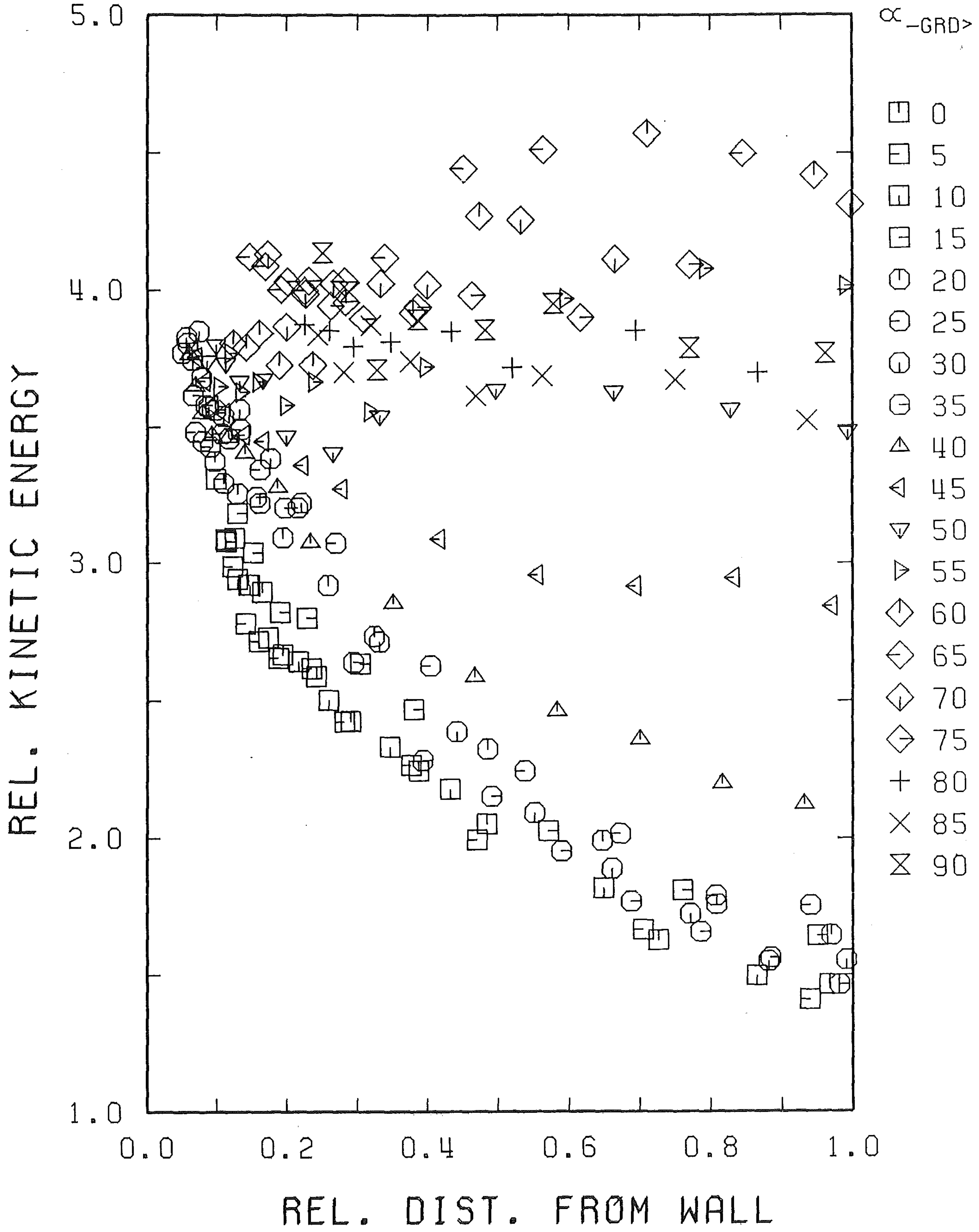


Fig. 19-2 Distribution of kinetic energy in the r/ϕ-part of quadrant 2

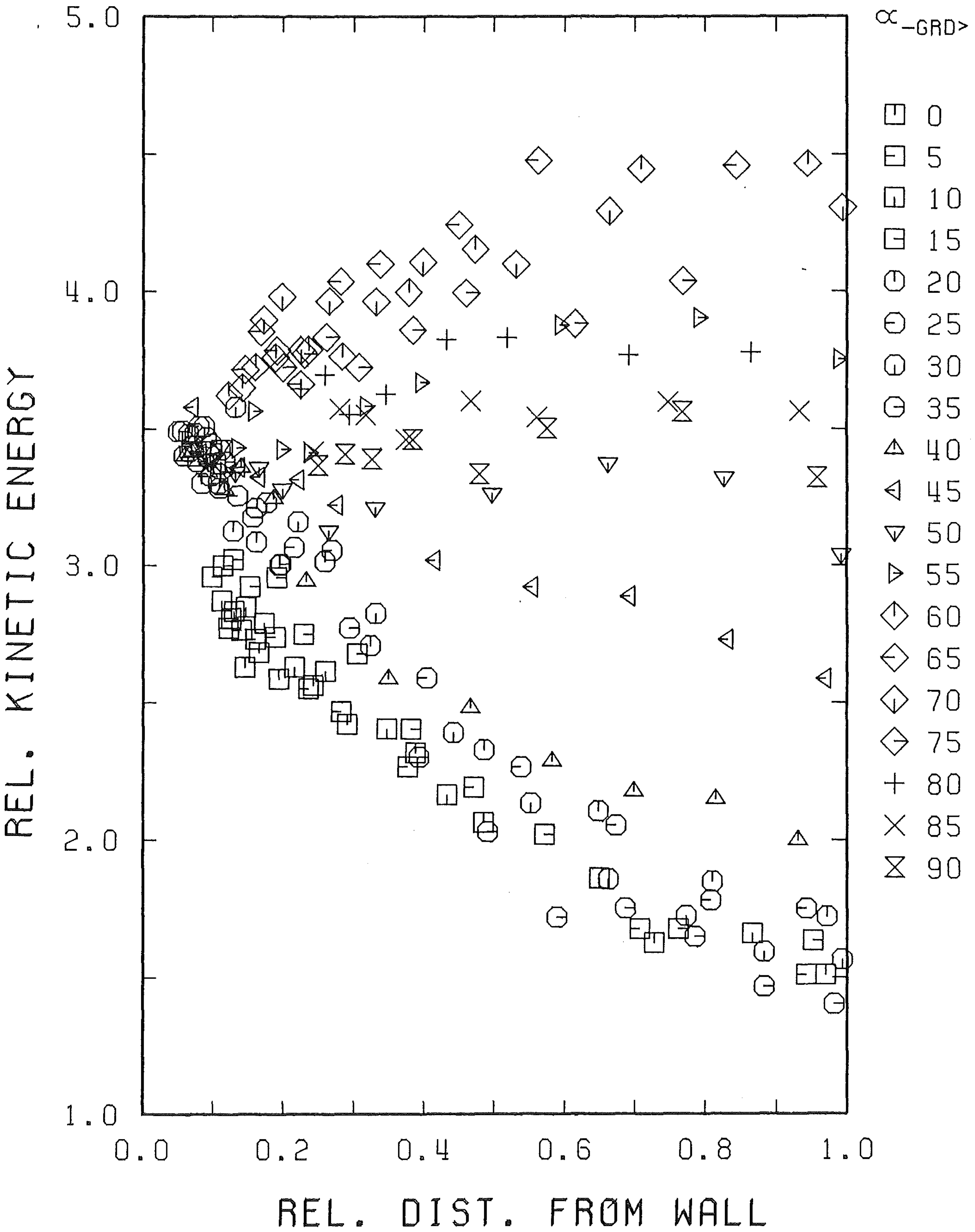
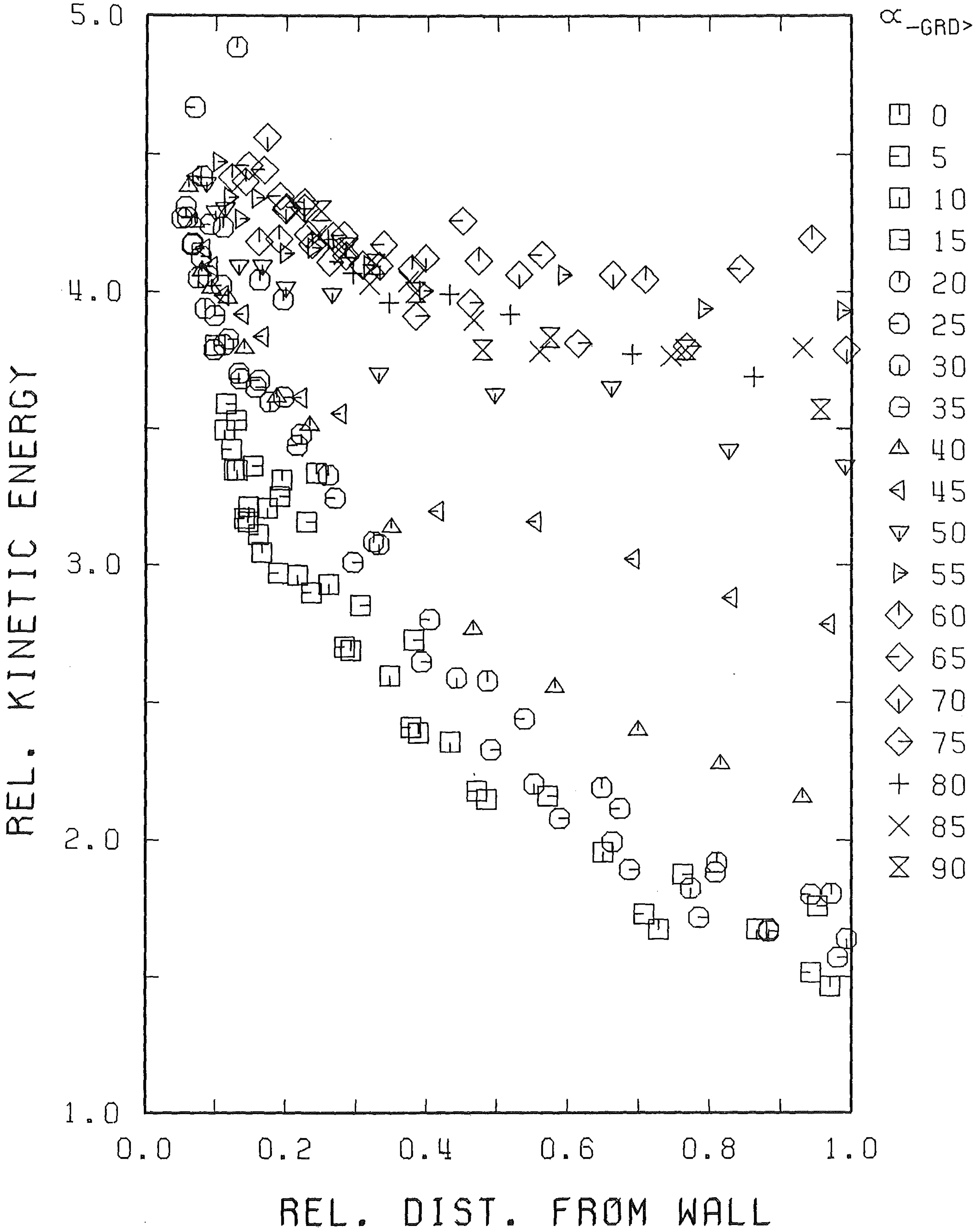


Fig. 19-3 Distribution of kinetic energy in the r/ϕ-part of quadrant 3



kfk

Fig. 19-4 Distribution of kinetic energy in the r/ϕ-part of quadrant 4

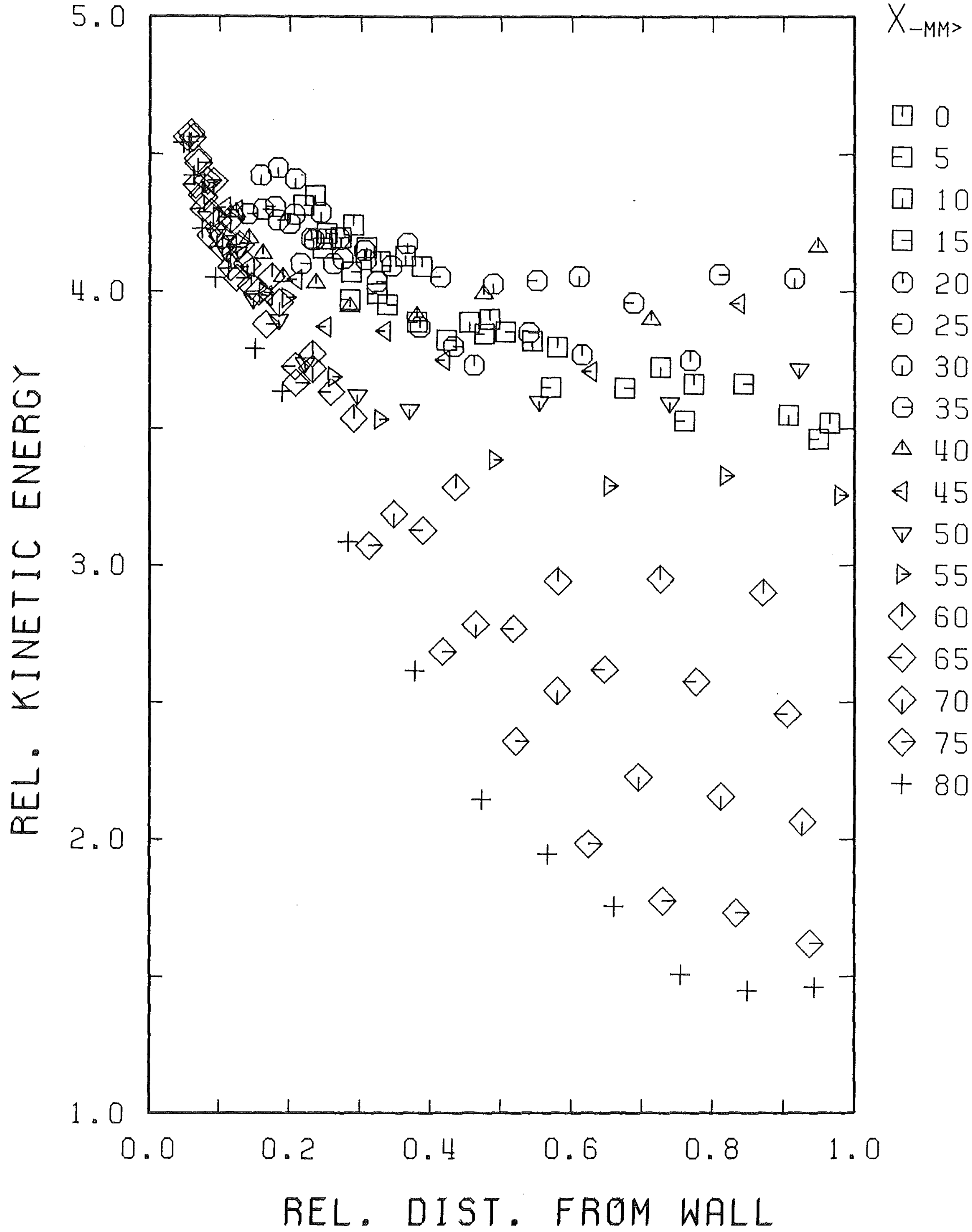


Fig. 20-1 Distribution of kinetic energy in the x/y-part of quadrant 1

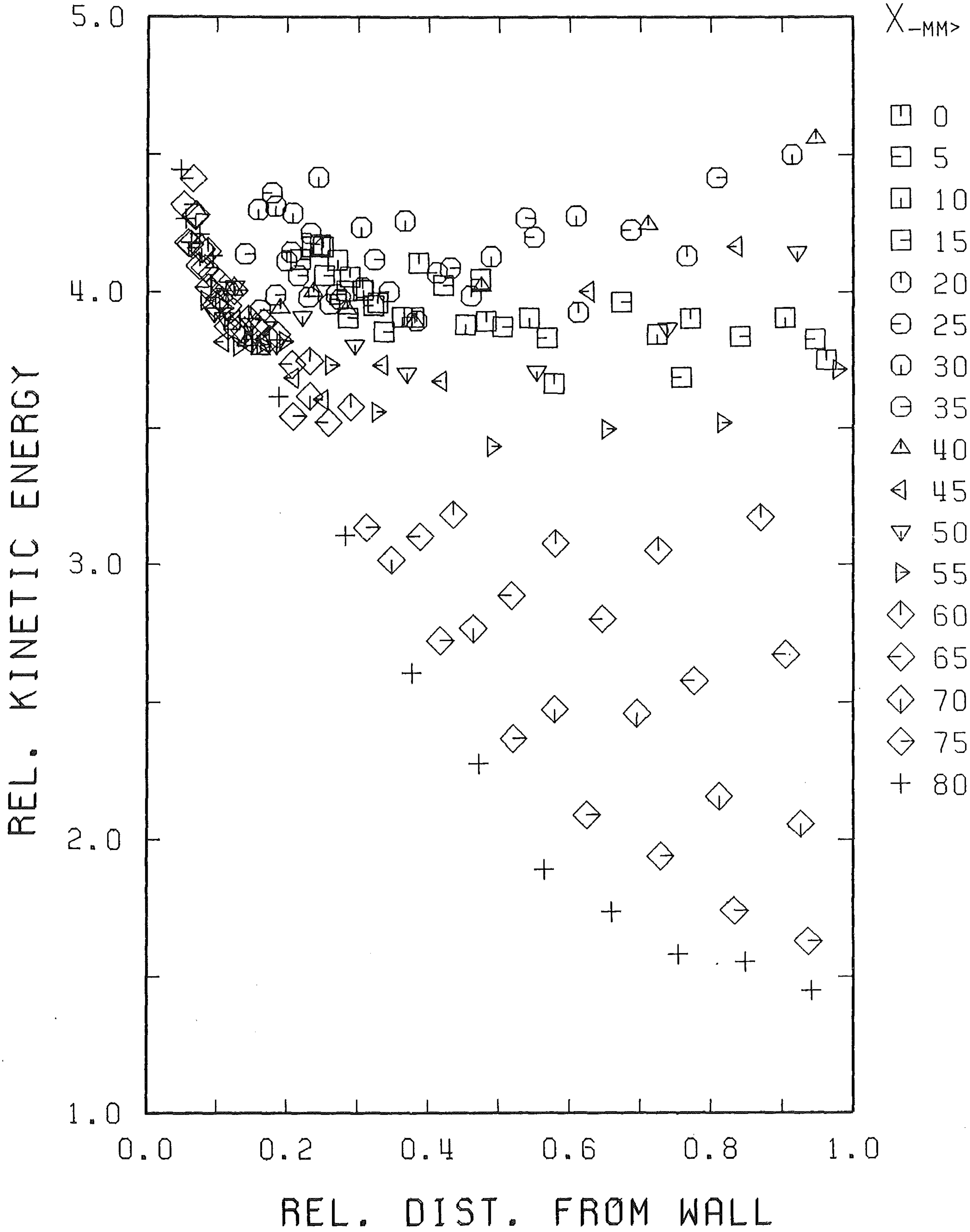


Fig. 20-2 Distribution of kinetic energy in the x/y-part of quadrant 2

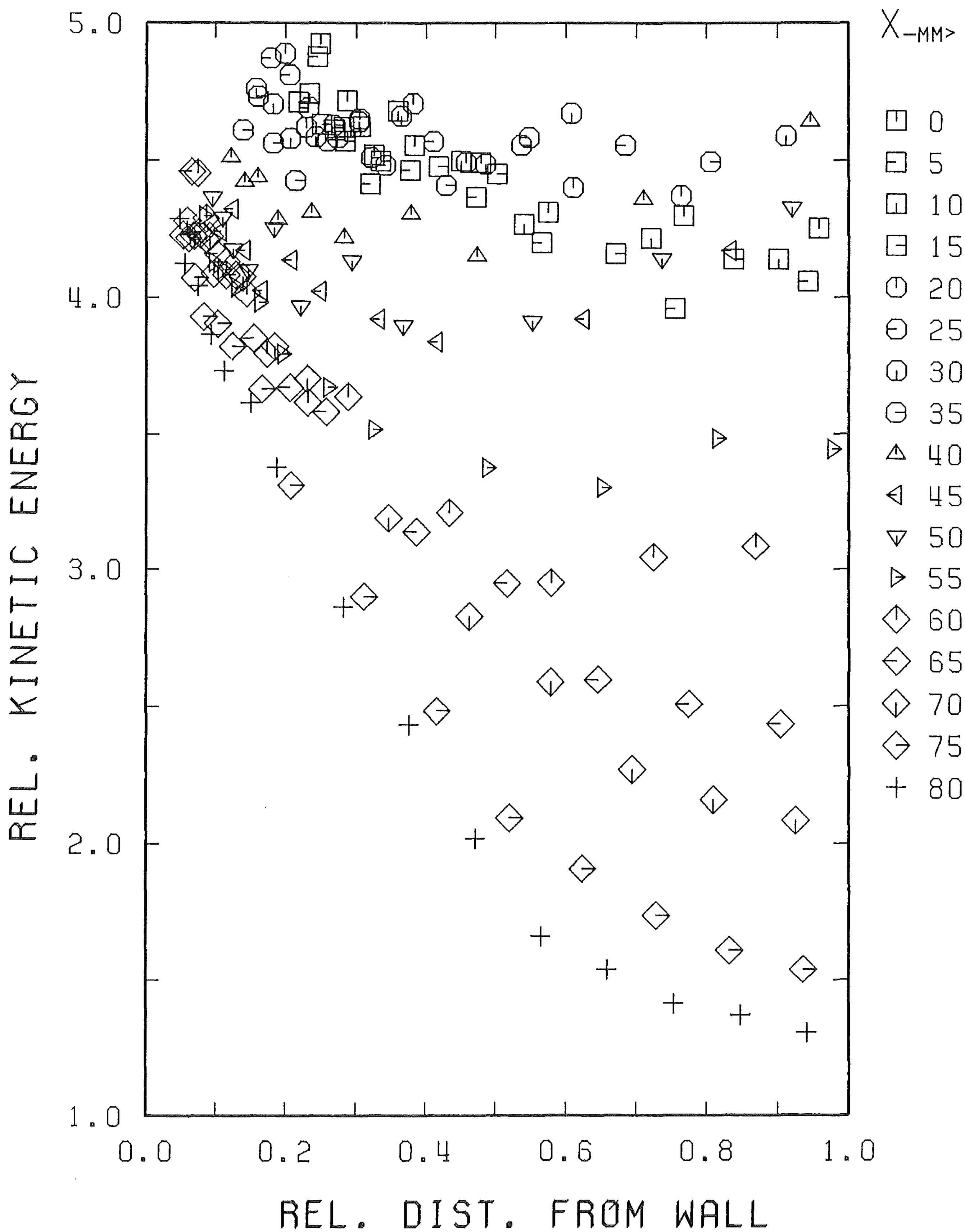


Fig. 20-3 Distribution of kinetic energy in the x/y-part of quadrant 3

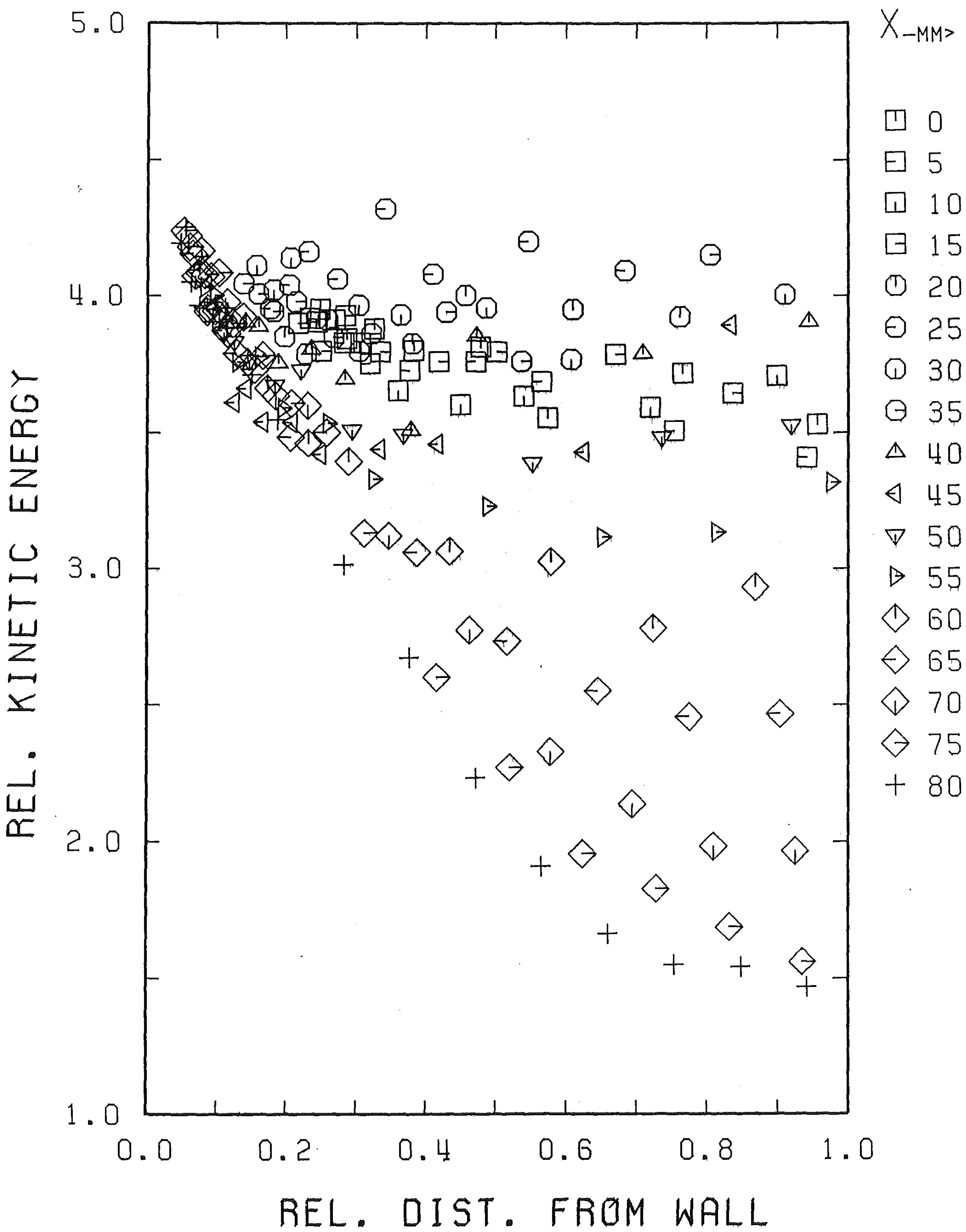


Fig. 20-4 Distribution of kinetic energy in the x/y-part of quadrant 4

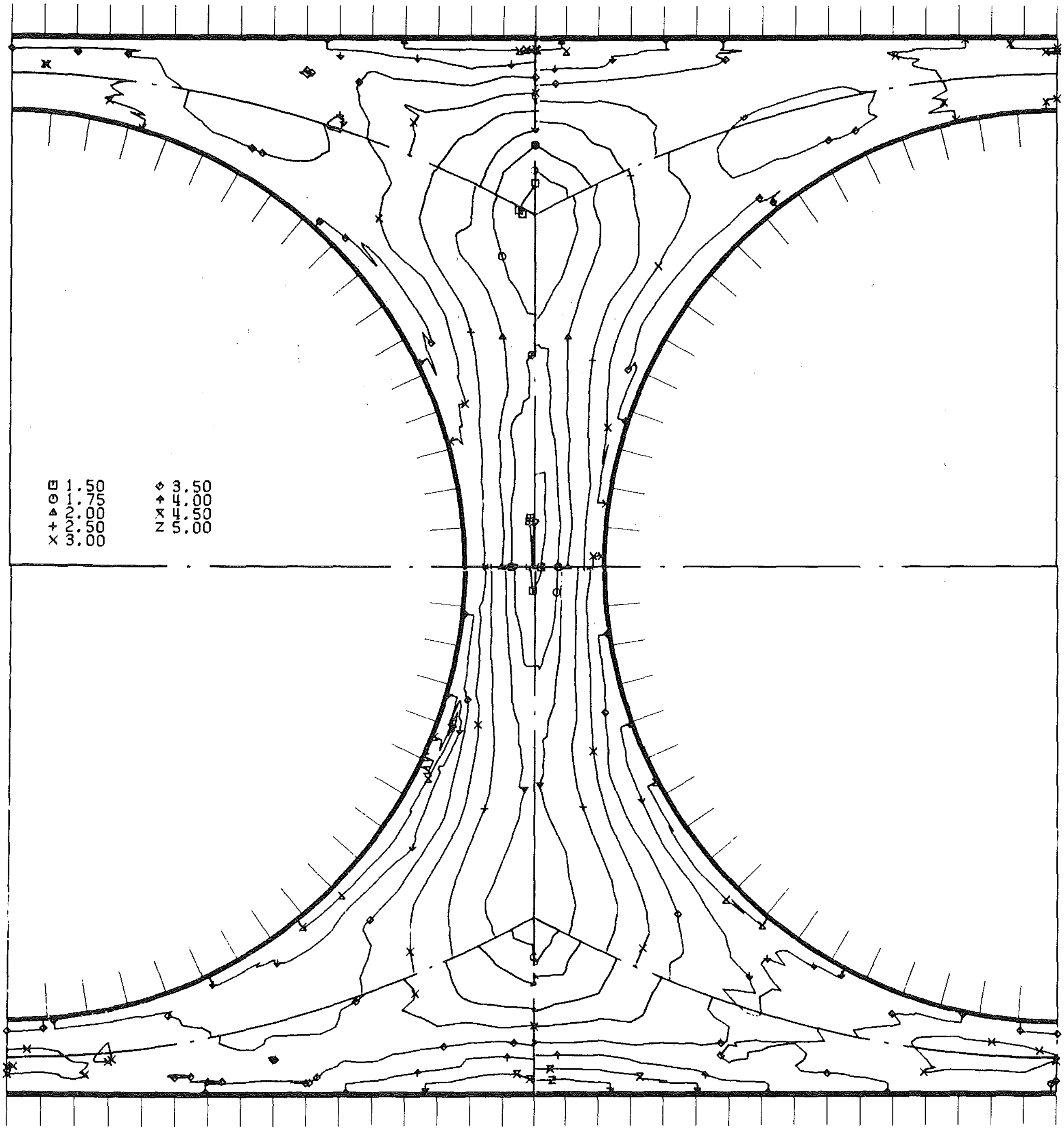


Fig. 21 Contours of kinetic energy in the four qudrants

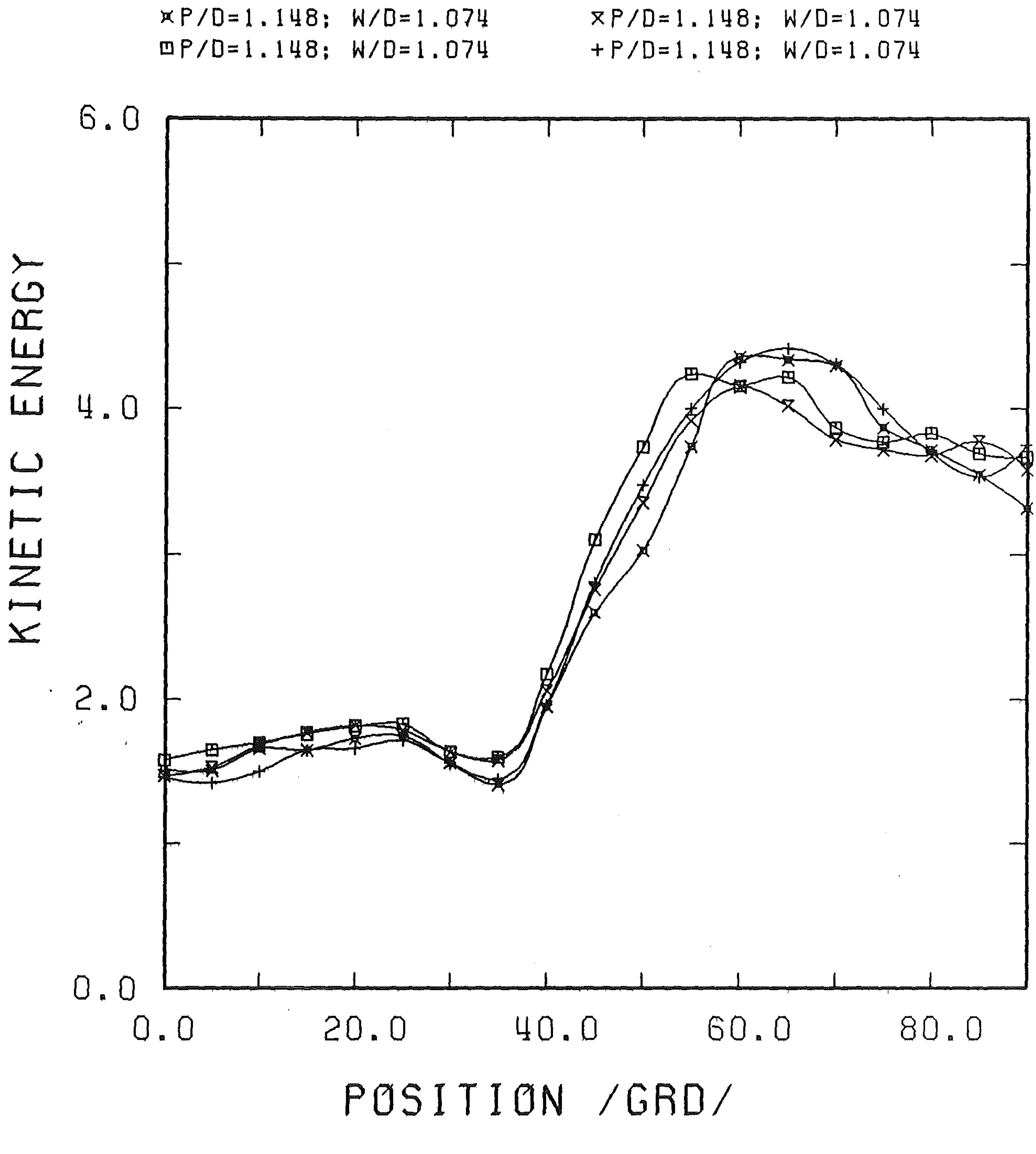


Fig. 21a Distribution of kinatic energy along the lines of maximum distance from the wall

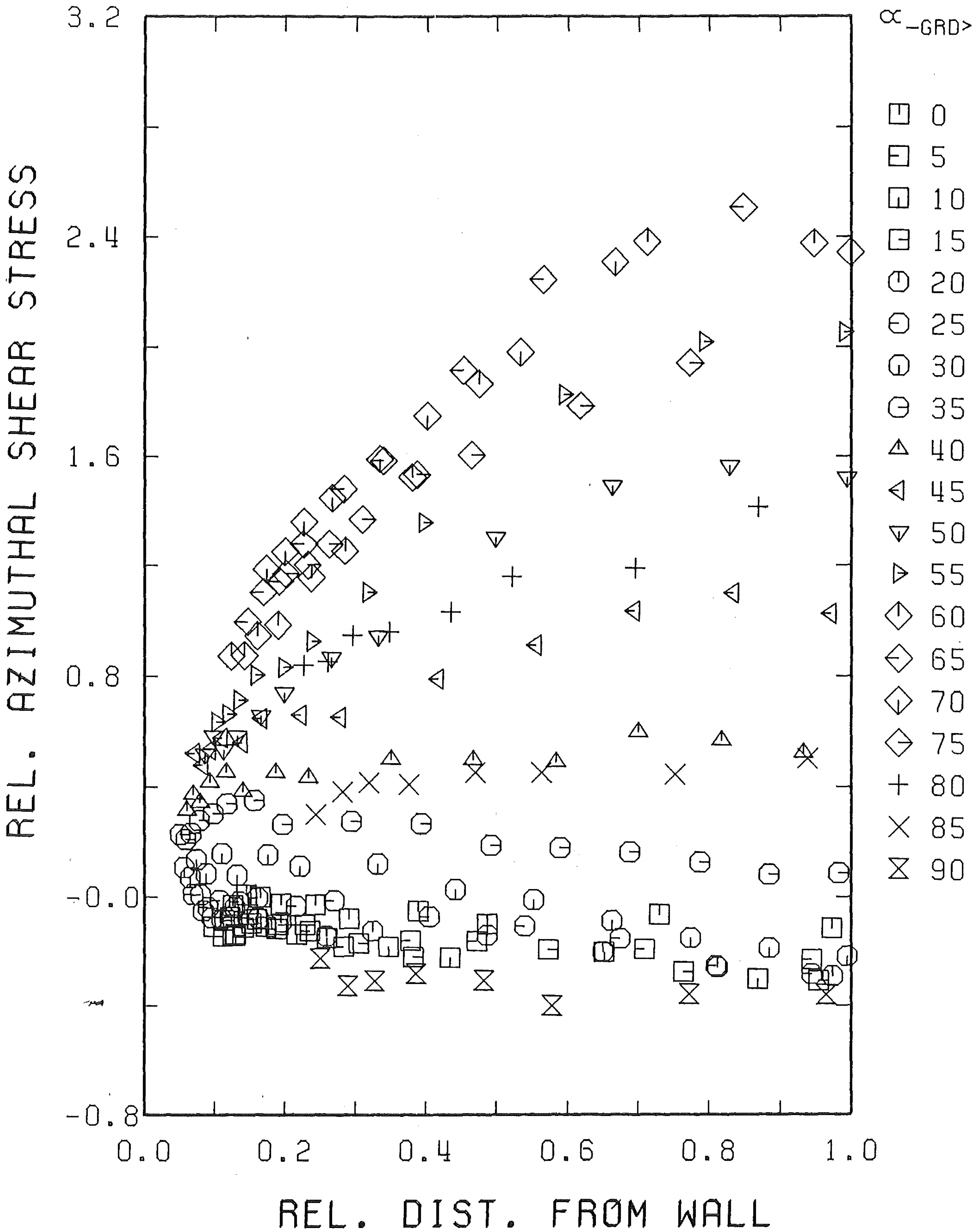


Fig. 22-1 Distribution of azimuthal shear stress
in the r/ϕ-part of quadrant 1

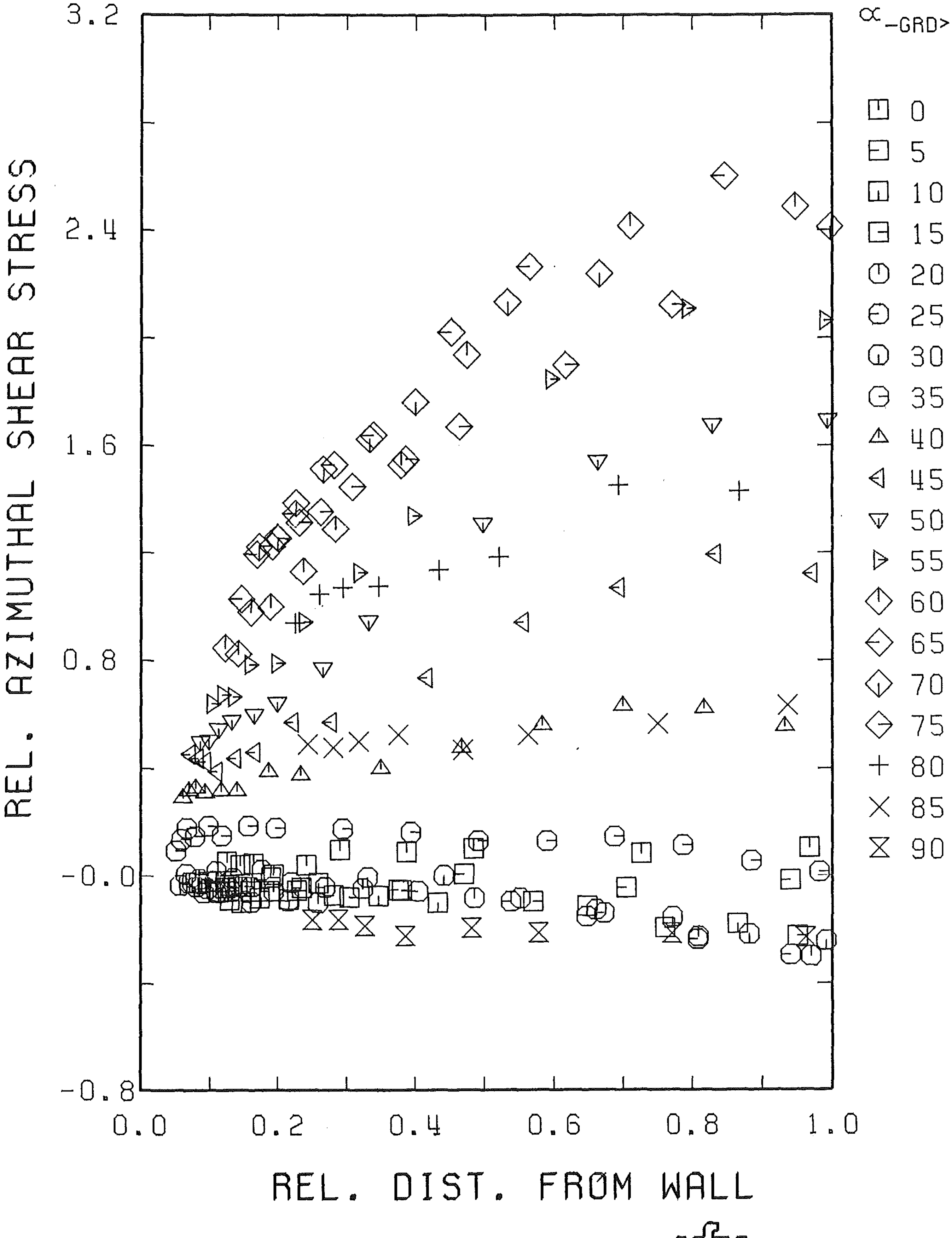


Fig. 22-2 Distribution of azimuthal shear stress
in the r/ϕ-part of quadrant 2

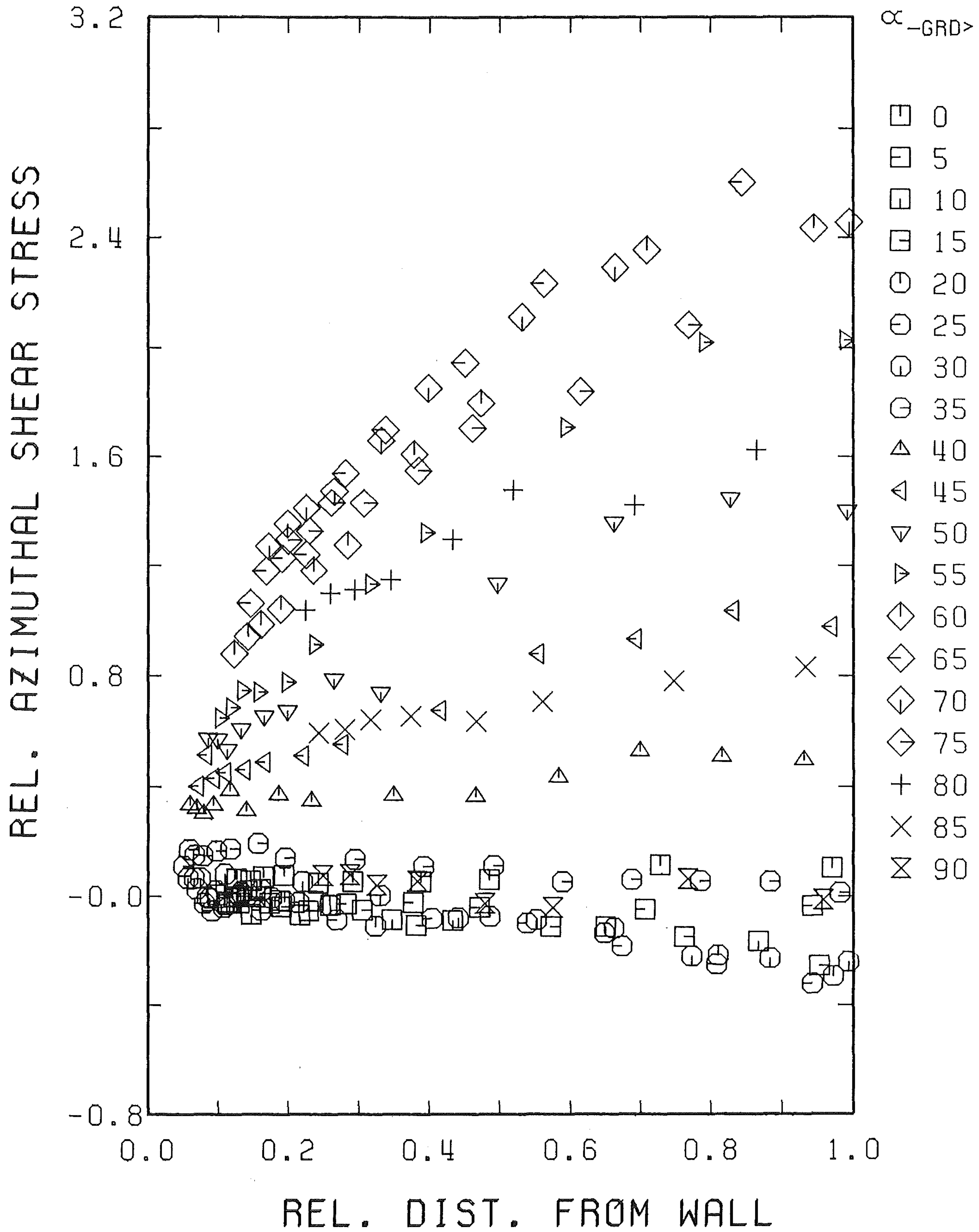


Fig. 22-3 Distribution of azimuthal shear stress
in the r/ϕ-part of quadrant 3

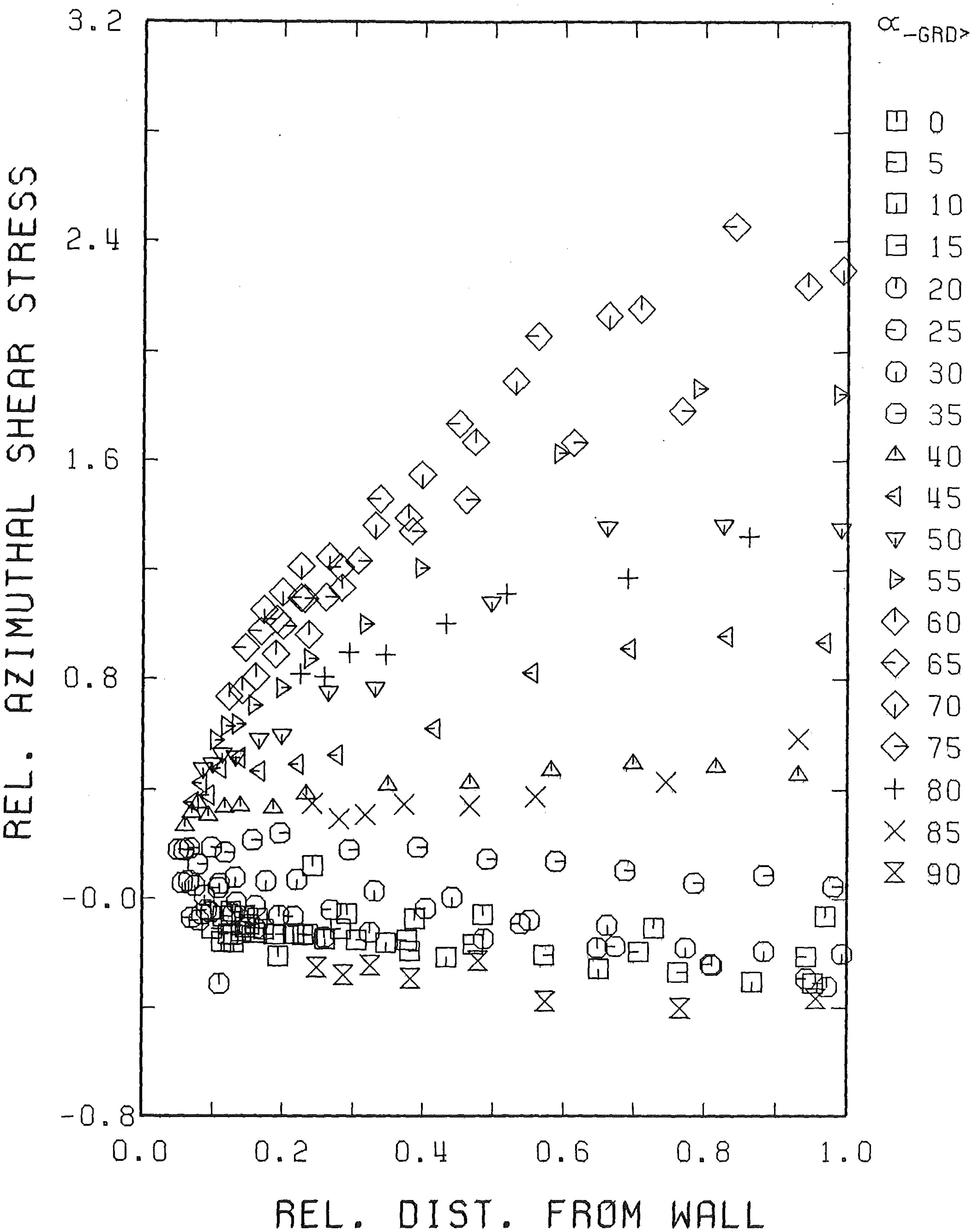


Fig. 22-4 Distribution of azimuthal shear stress
in the r/ϕ-part of quadrant 4

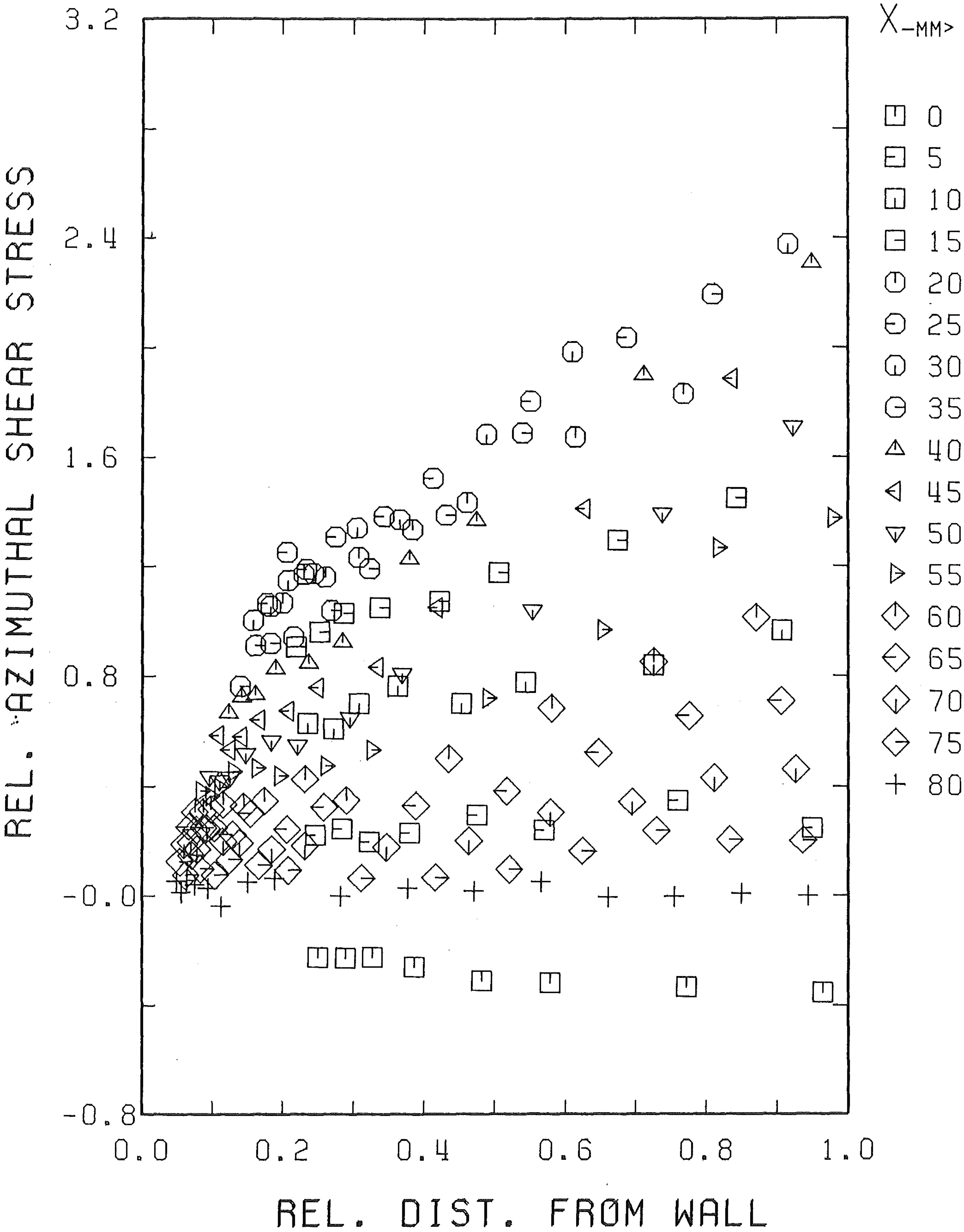


Fig. 23-1 Distribution of azimuthal shear stress
in the x/y-part of quadrant 1

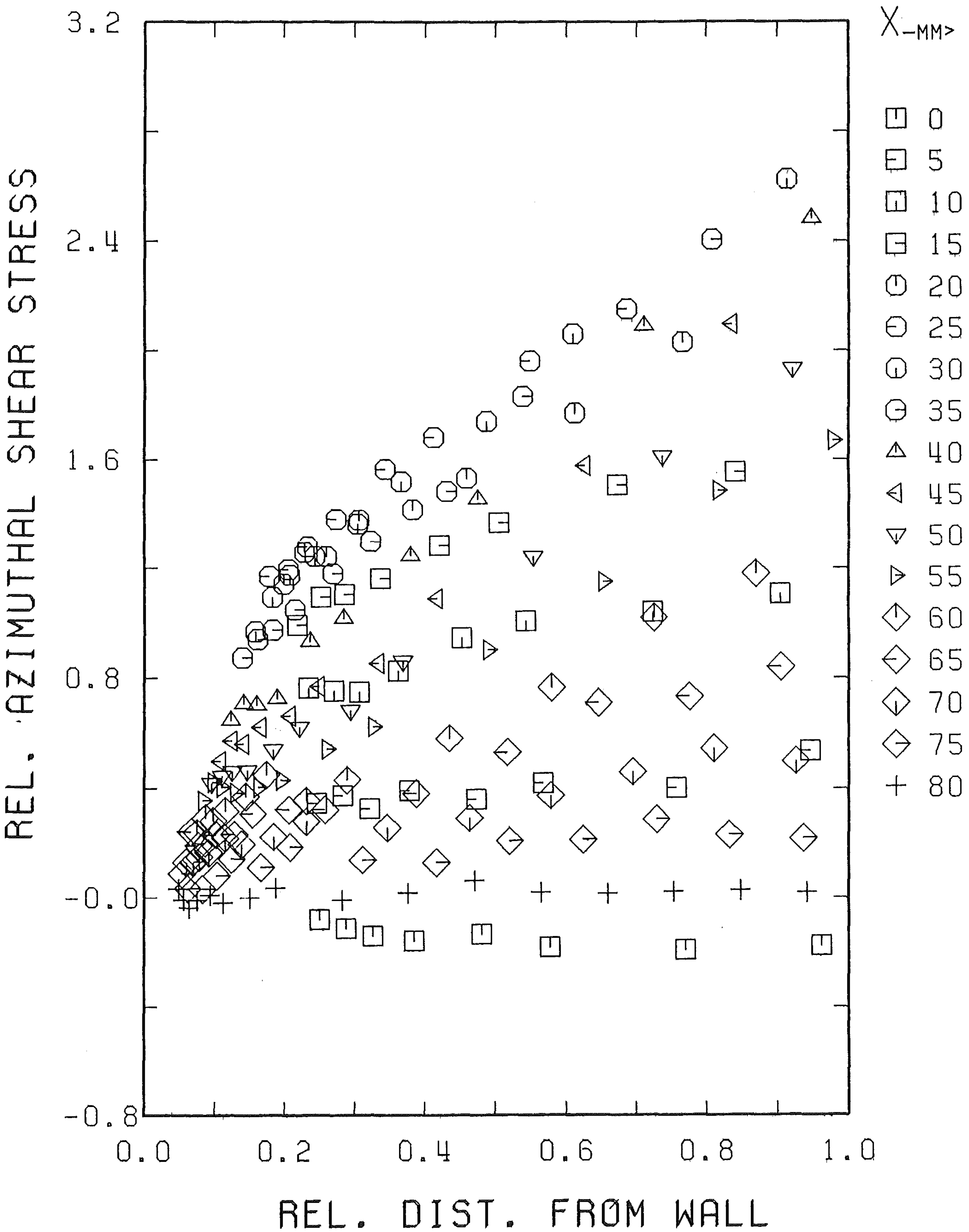


Fig. 23-2 Distribution of azimuthal shear stress
in the x/y-part of quadrant 2

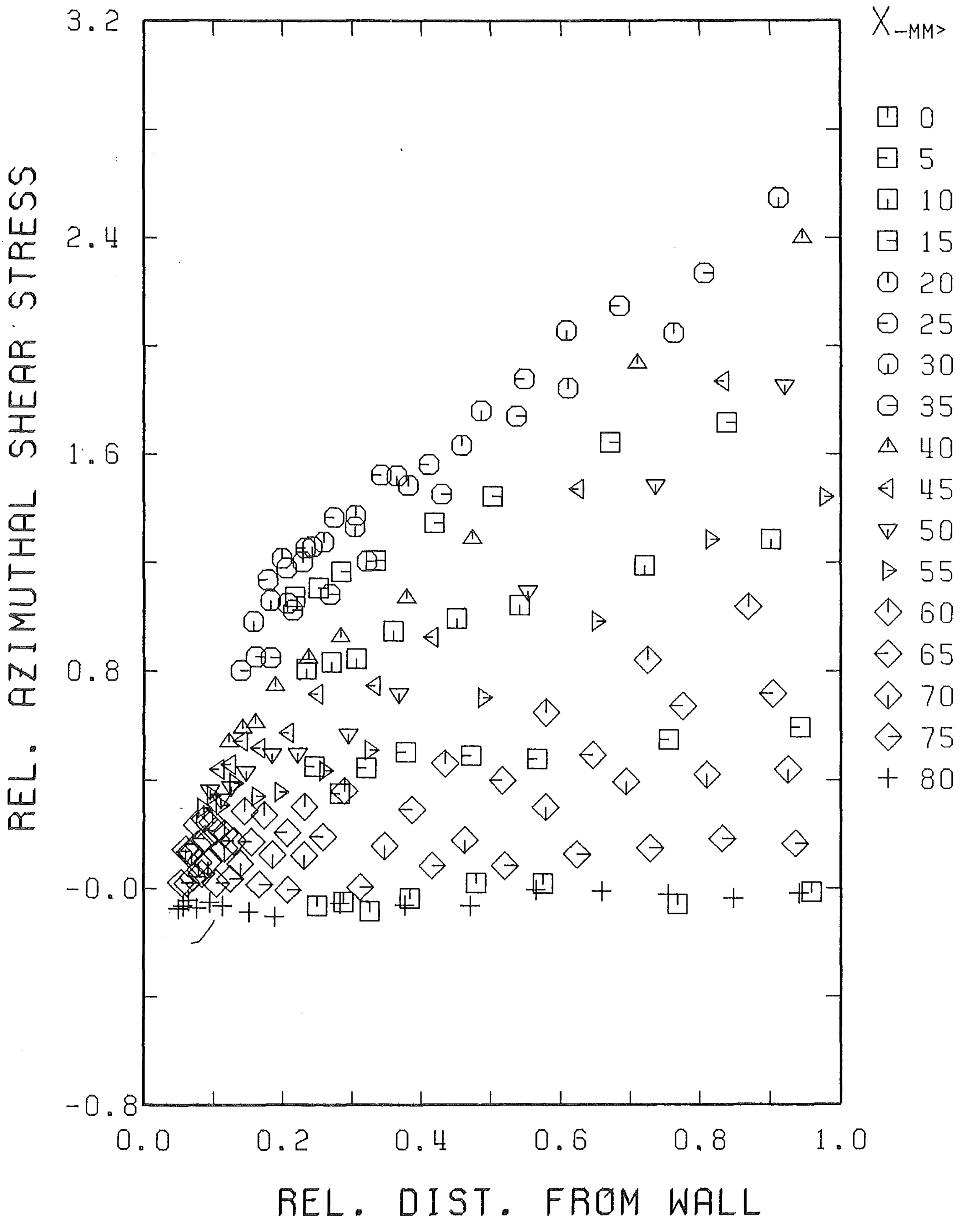


Fig. 23-3 Distribution of azimuthal shear stress in the x/y-part of quadrant 3

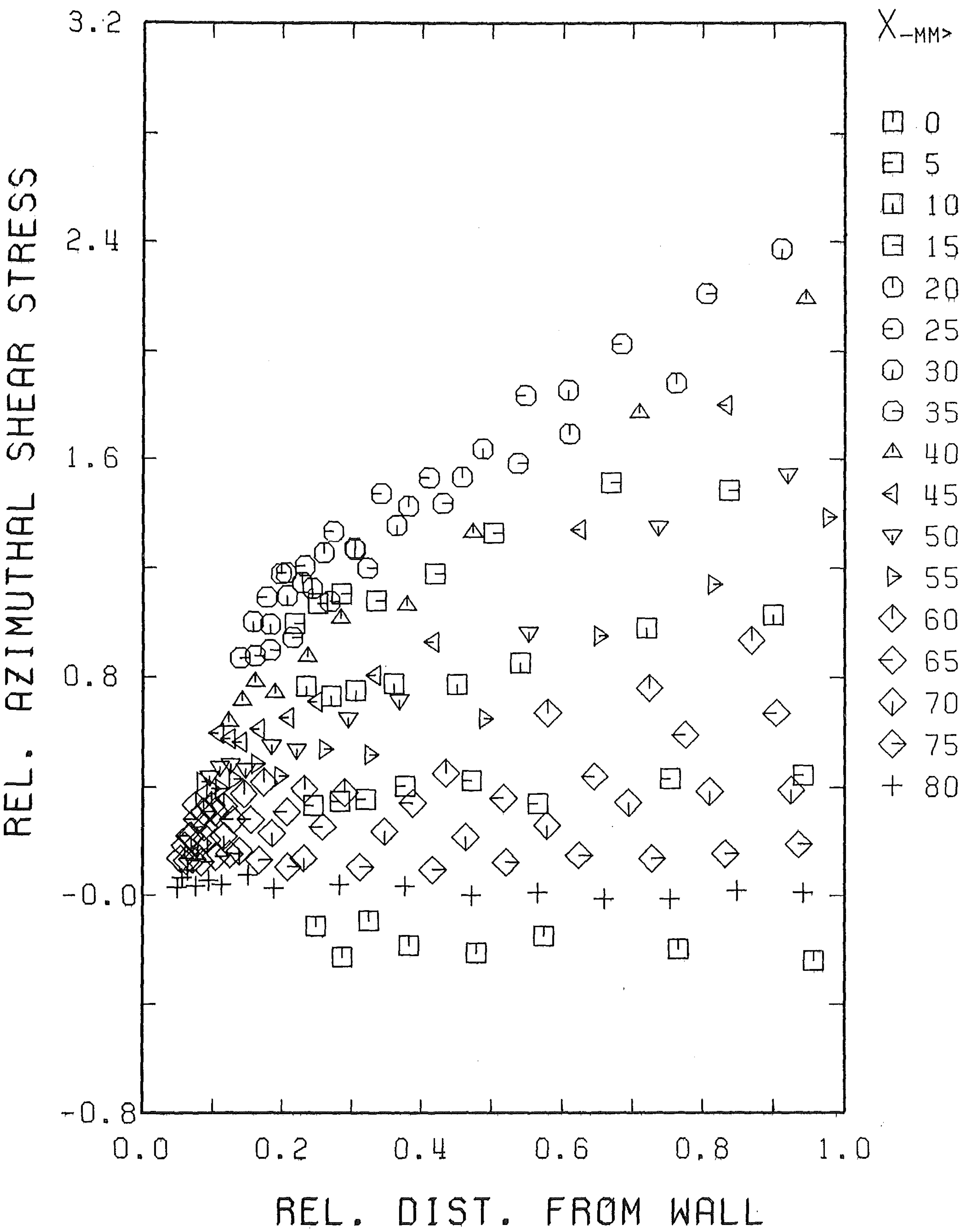


Fig. 23-4 Distribution of azimuthal shear stress
in the x/y-part of quadrant 4

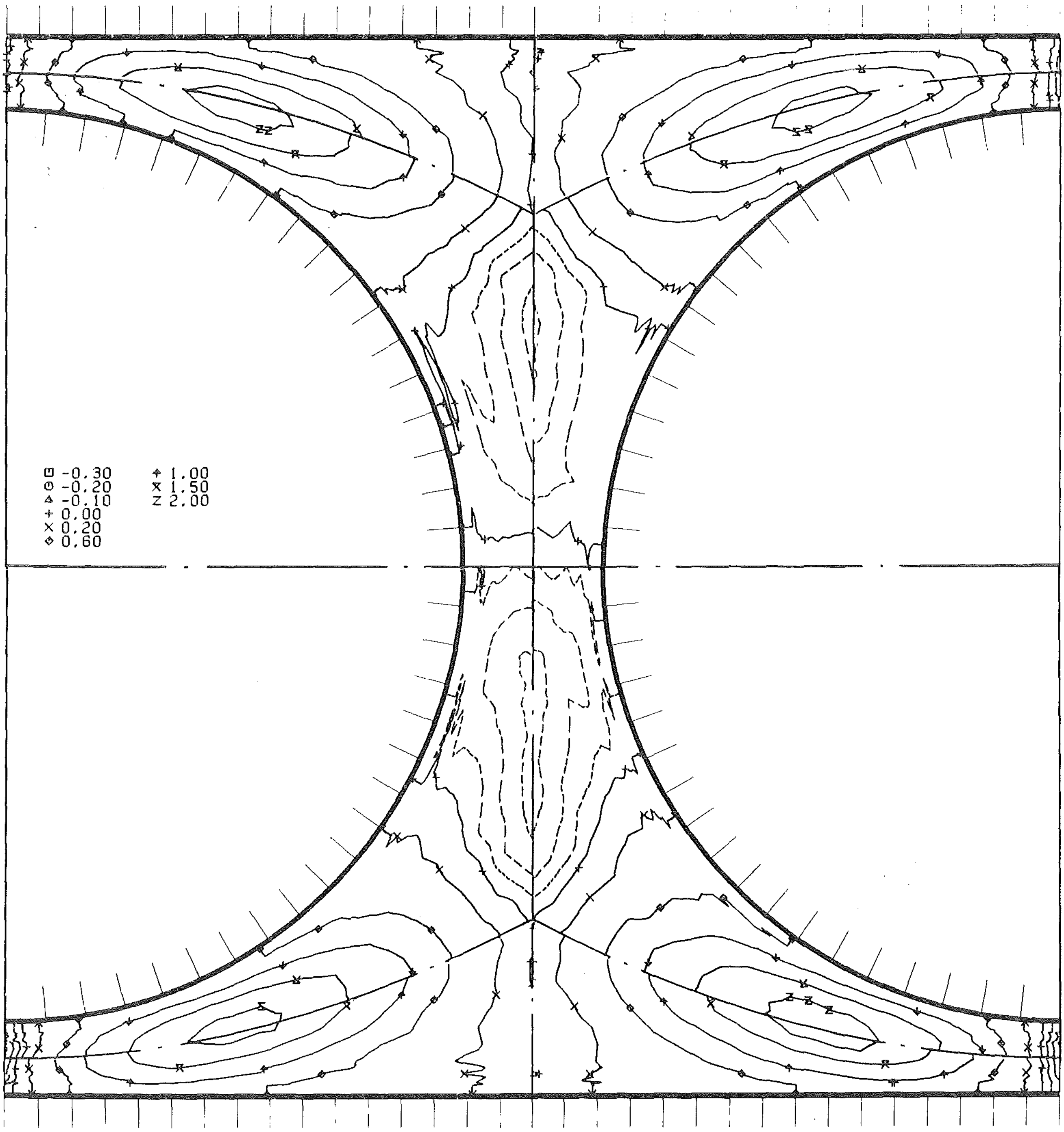


Fig. 24 Contours of azimuthal shear stress in the four qudrants

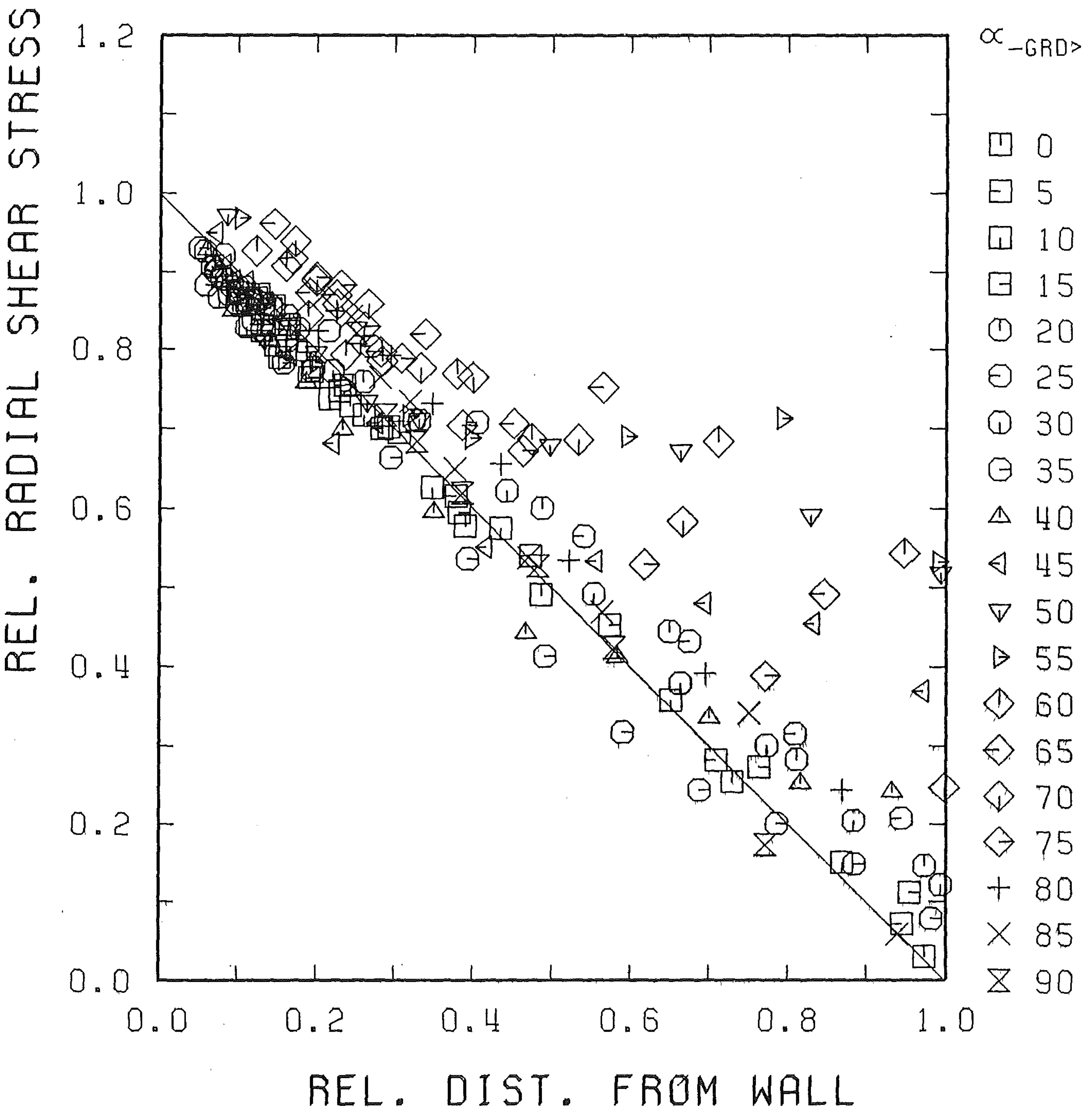


Fig. 25-1 Distribution of radial shear stress
in the r/ϕ-part of quadrant 1

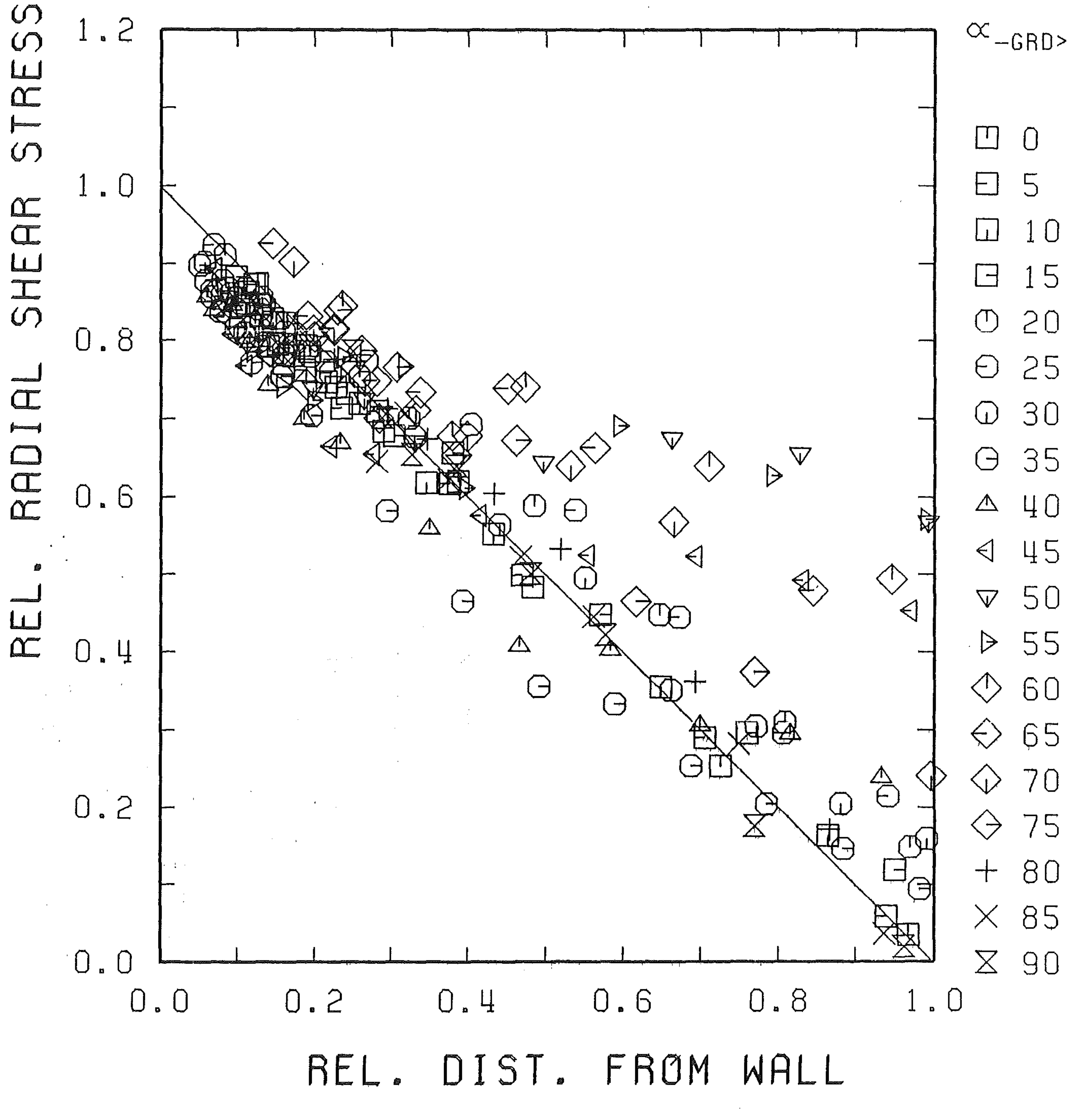


Fig. 25-2 Distribution of radial shear stress
in the r/ϕ-part of quadrant 2

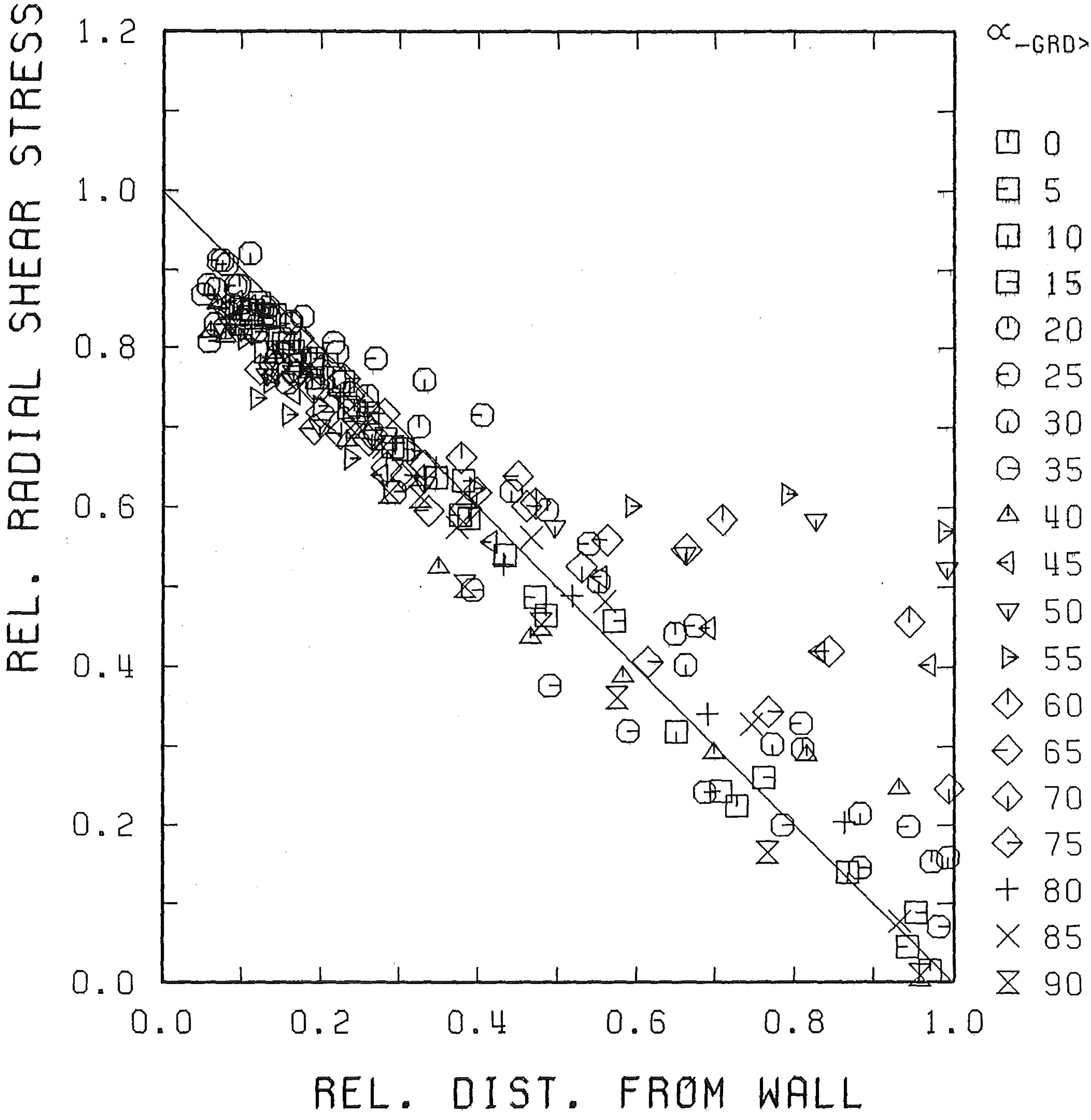


Fig. 25-3 Distribution of radial shear stress
in the r/ϕ-part of quadrant 3

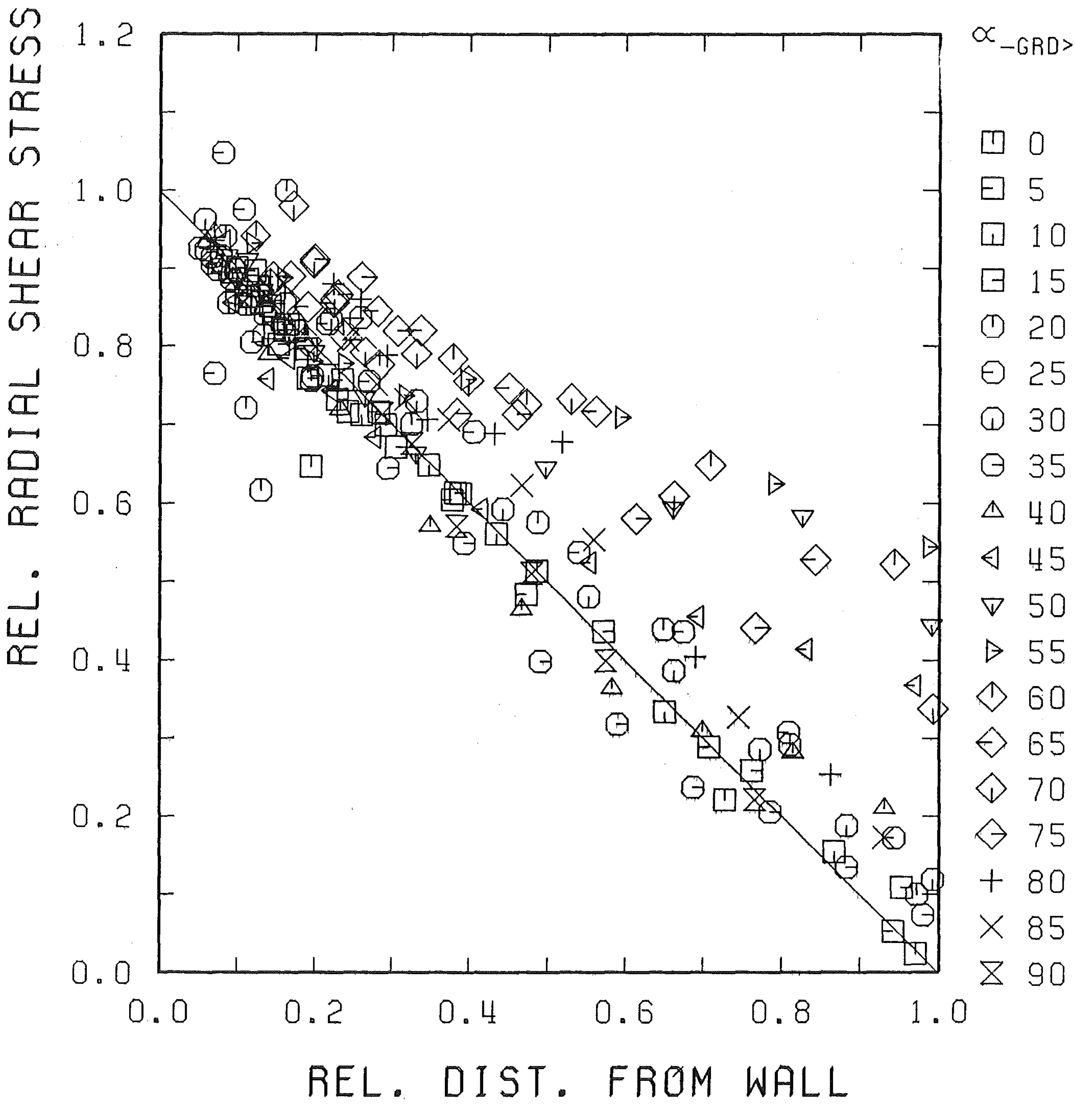


Fig. 25-4 Distribution of radial shear stress
in the r/ϕ-part of quadrant 4

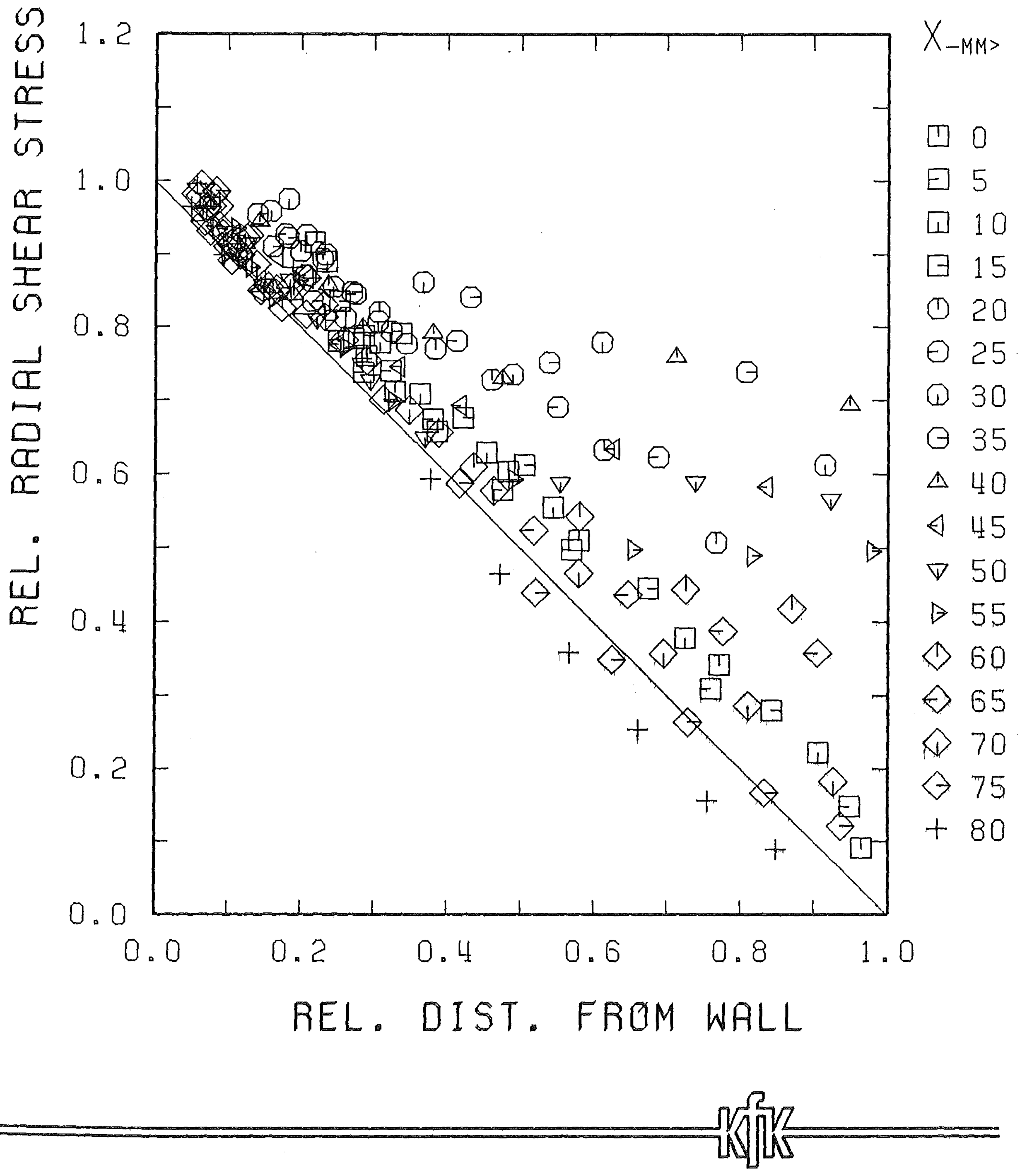


Fig. 26-1 Distribution of radial shear stress
in the x/y-part of quadrant 1

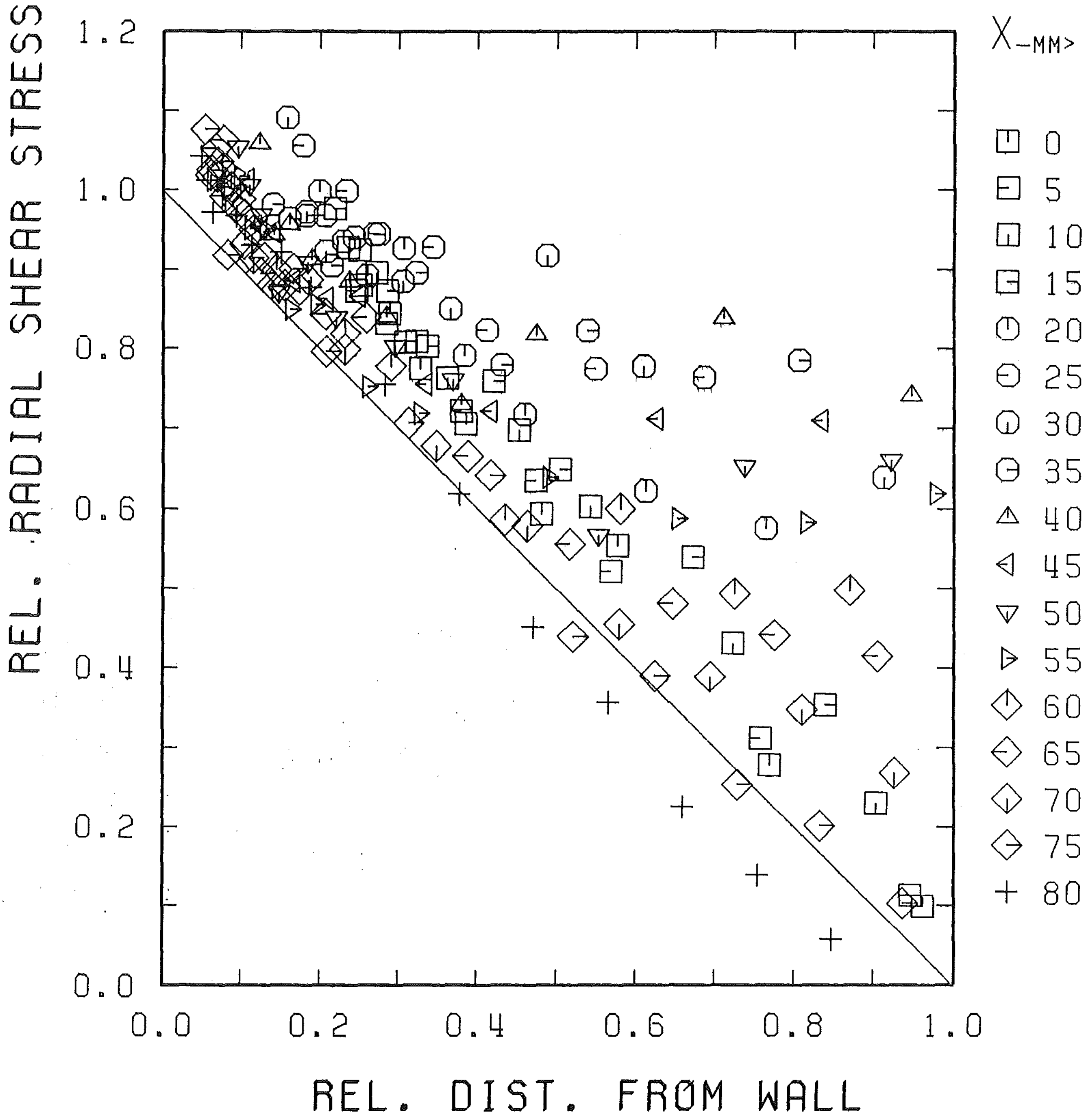


Fig. 26-2 Distribution of radial shear stress
in the x/y-part of quadrant 2

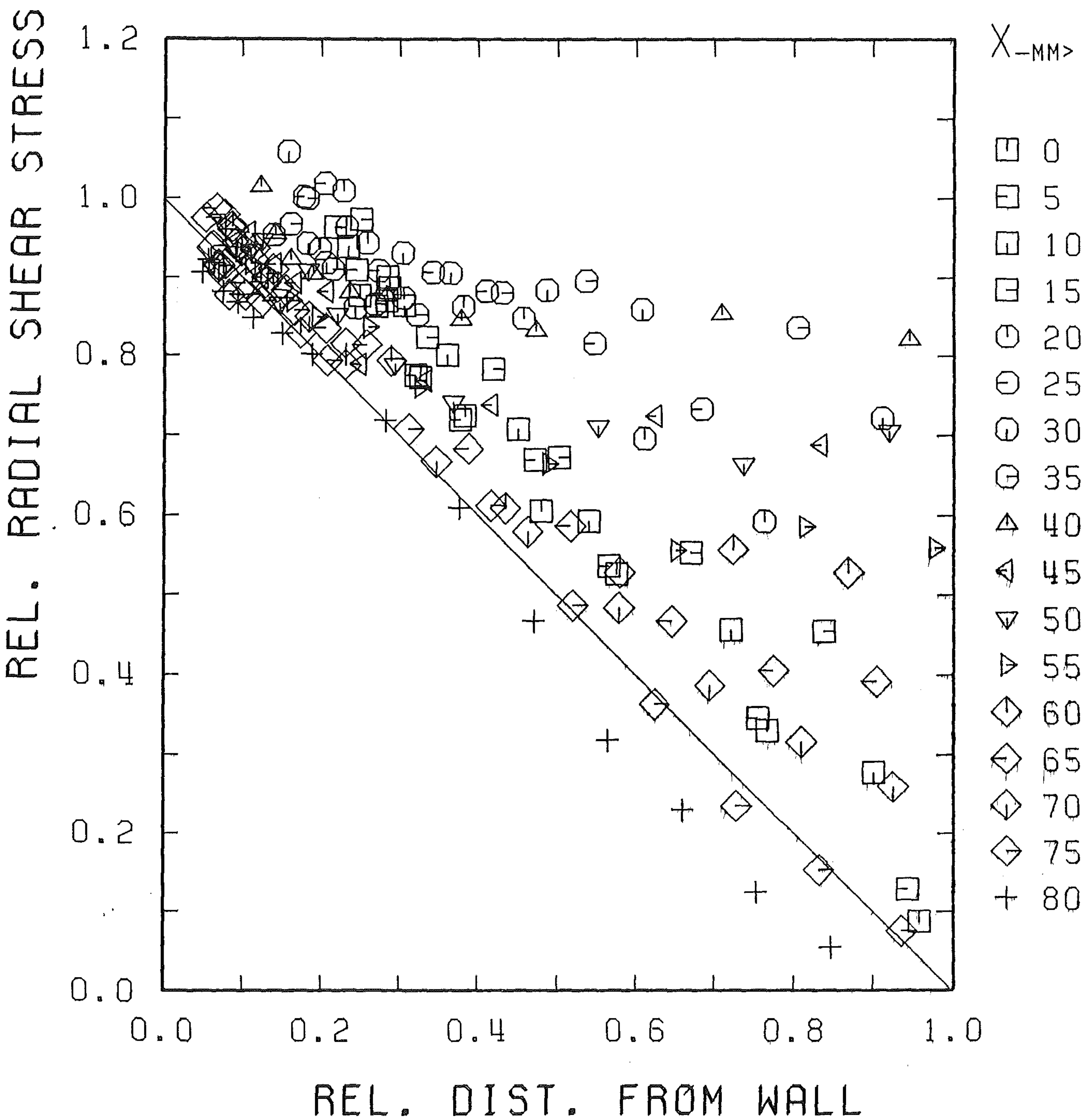


Fig. 26-3 Distribution of radial shear stress
in the x/y-part of quadrant 3

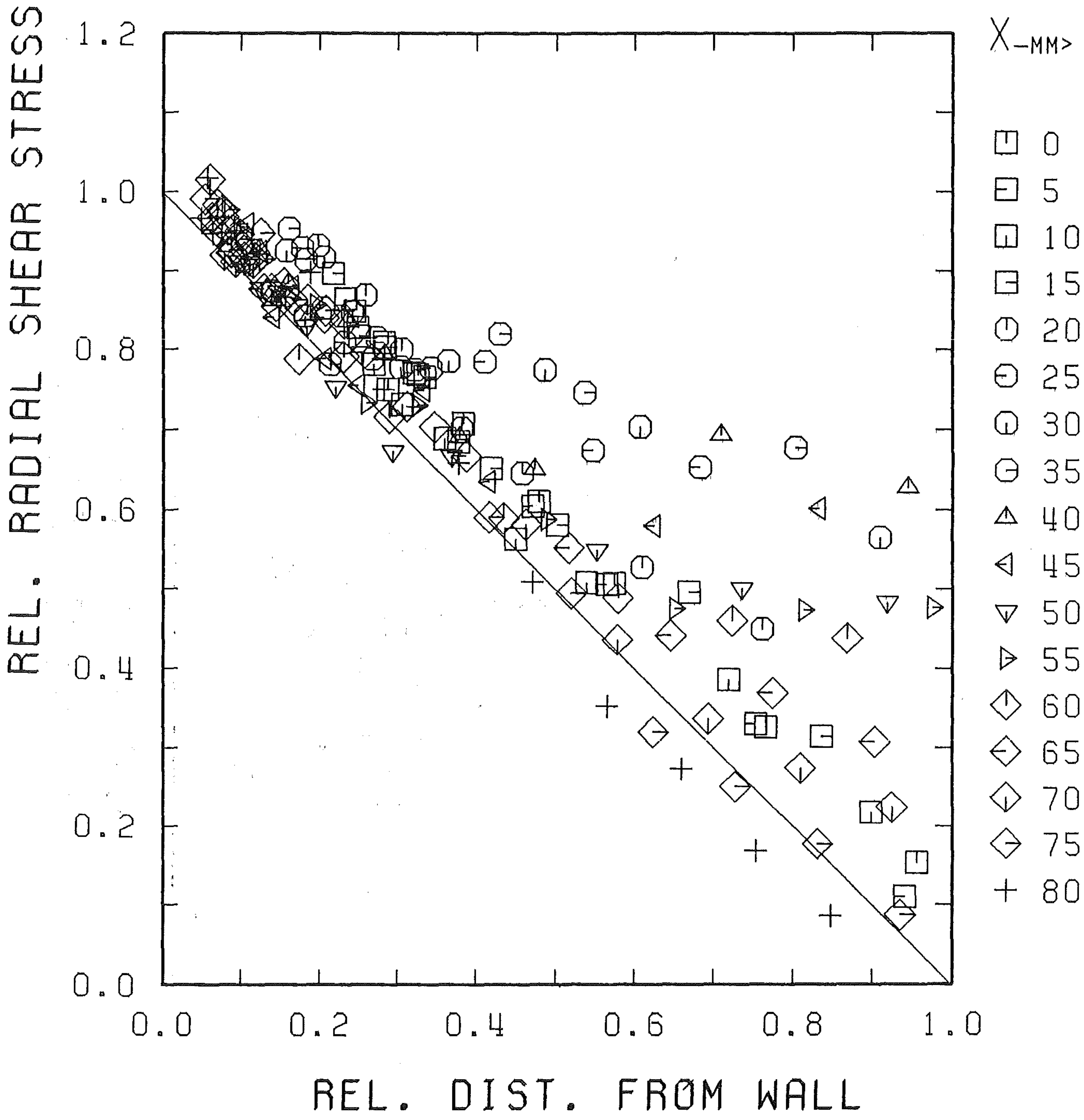


Fig. 26-4 Distribution of radial shear stress
in the x/y-part of quadrant 4

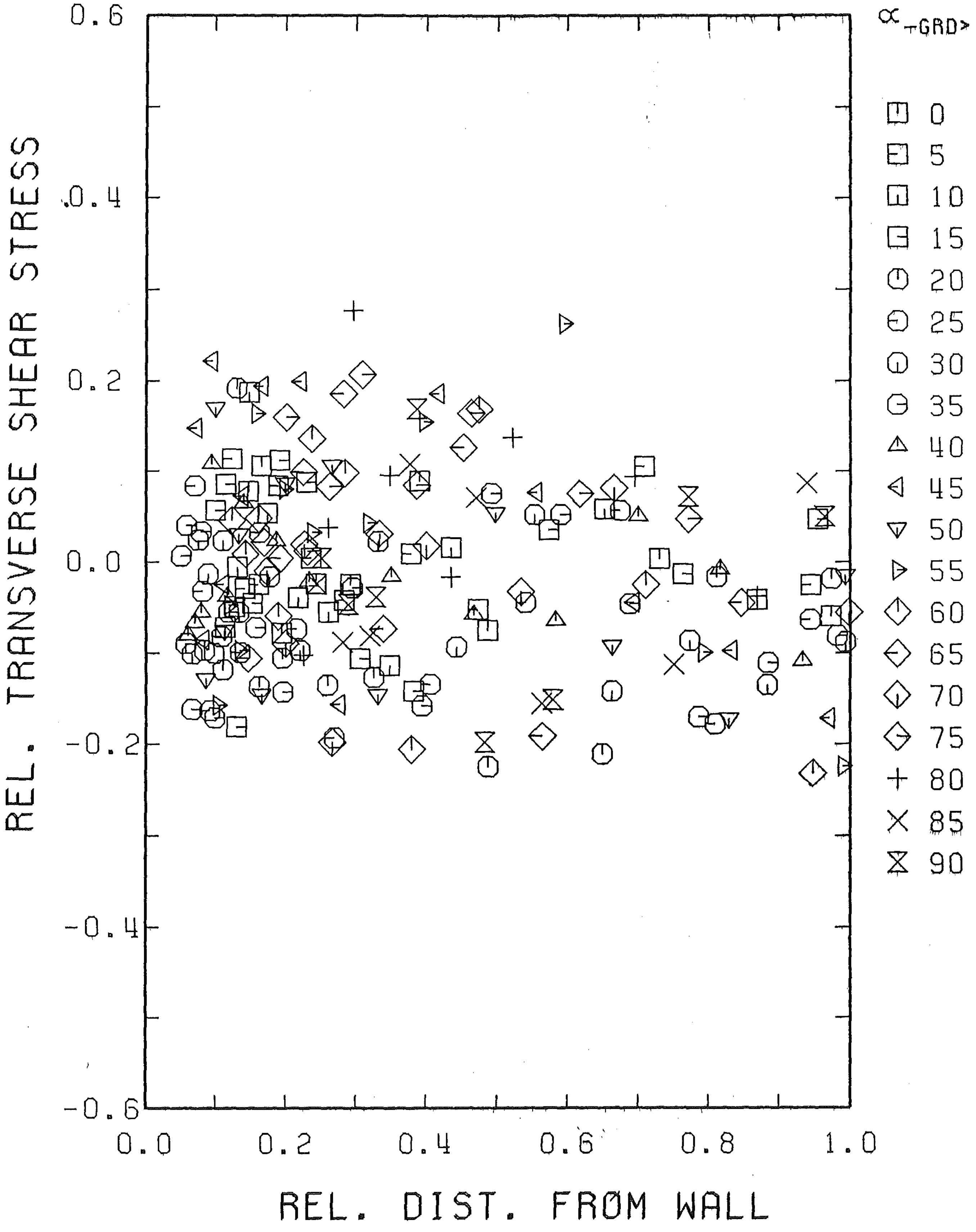


Fig. 27-1 Distribution of transverse shear stress in the r/ϕ-part of quadrant 1

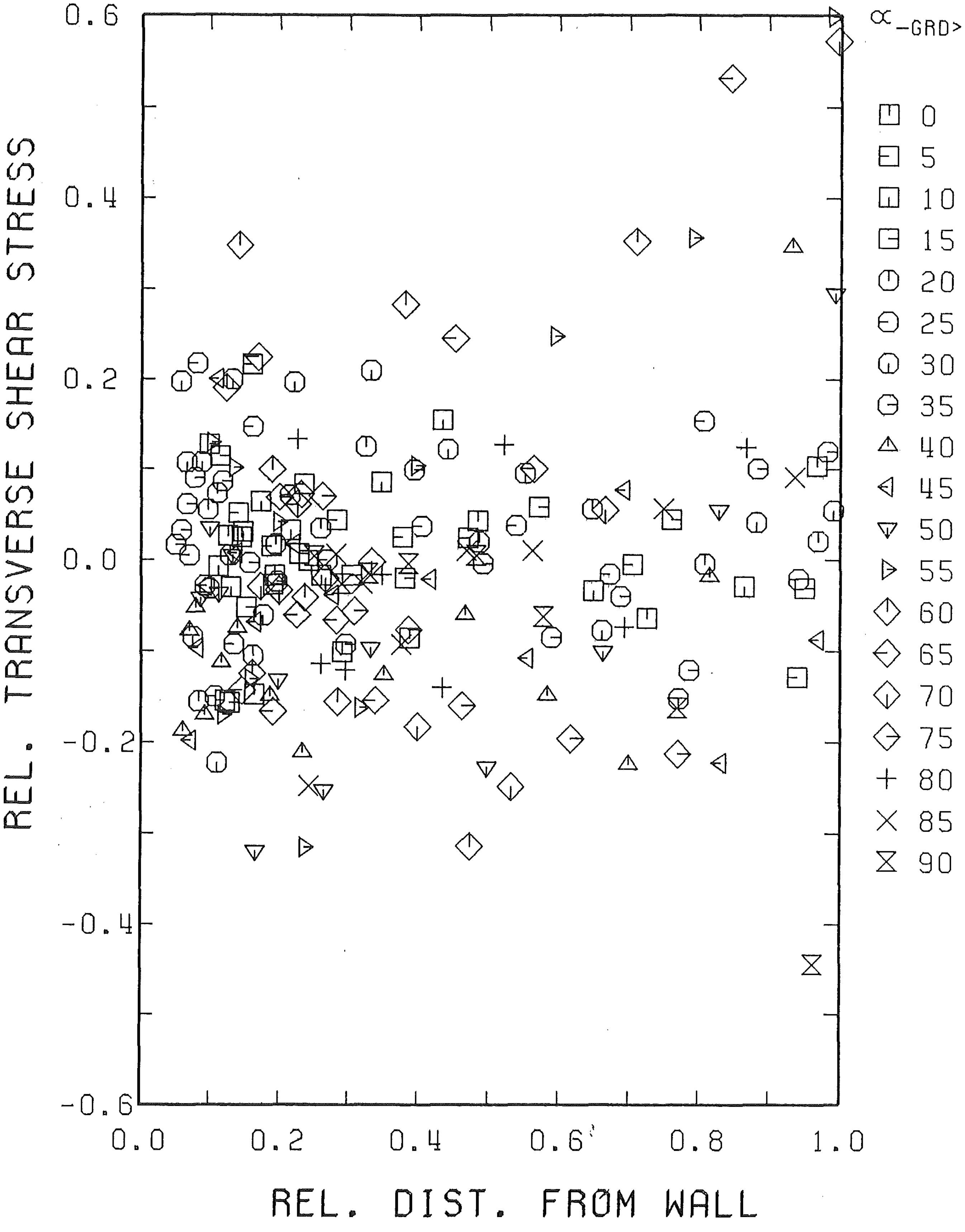


Fig. 27-2 Distribution of transverse shear stress in the r/ϕ-part of quadrant 2

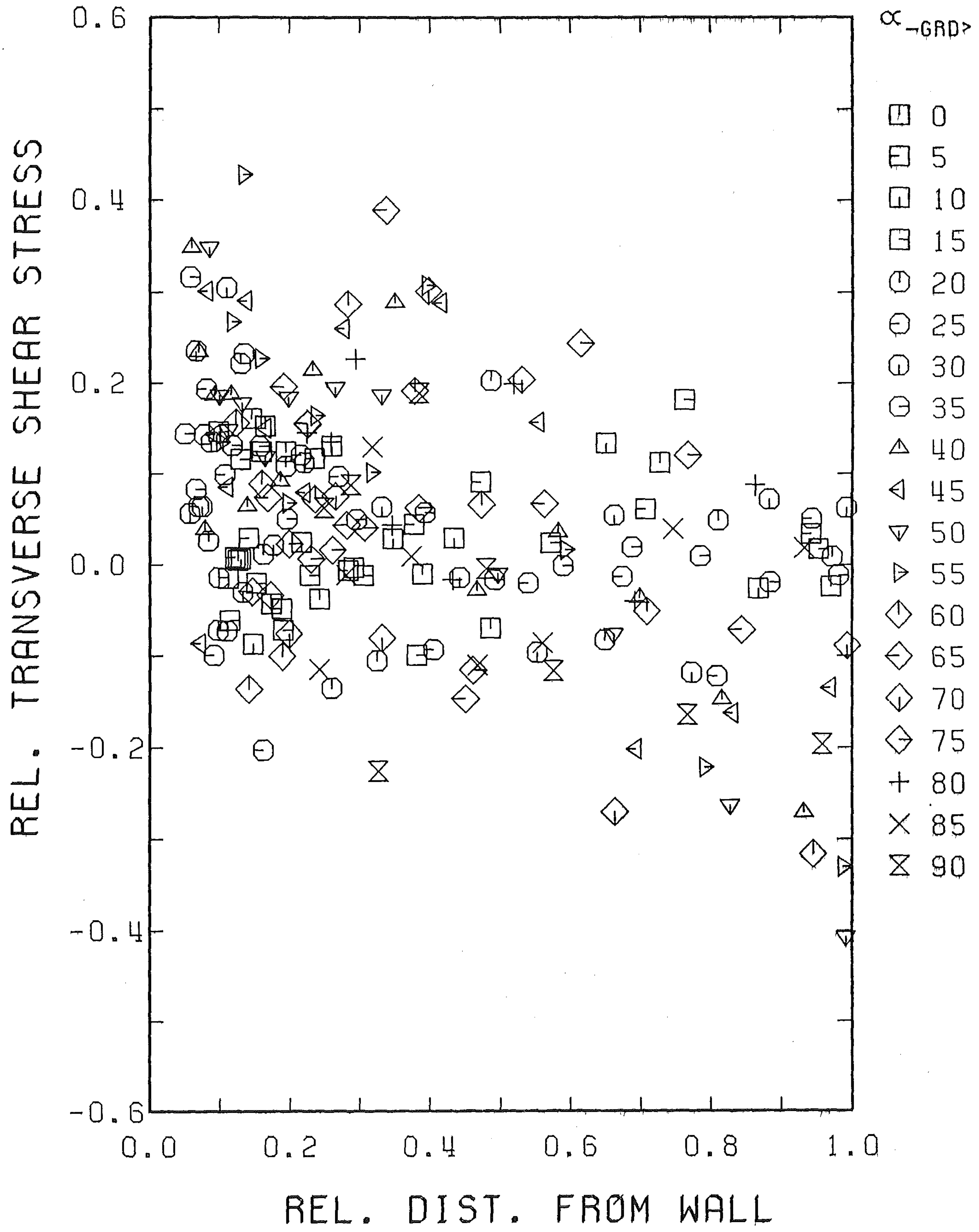


Fig. 27-3 Distribution of transverse shear stress
in the r/ϕ-part of quadrant 3

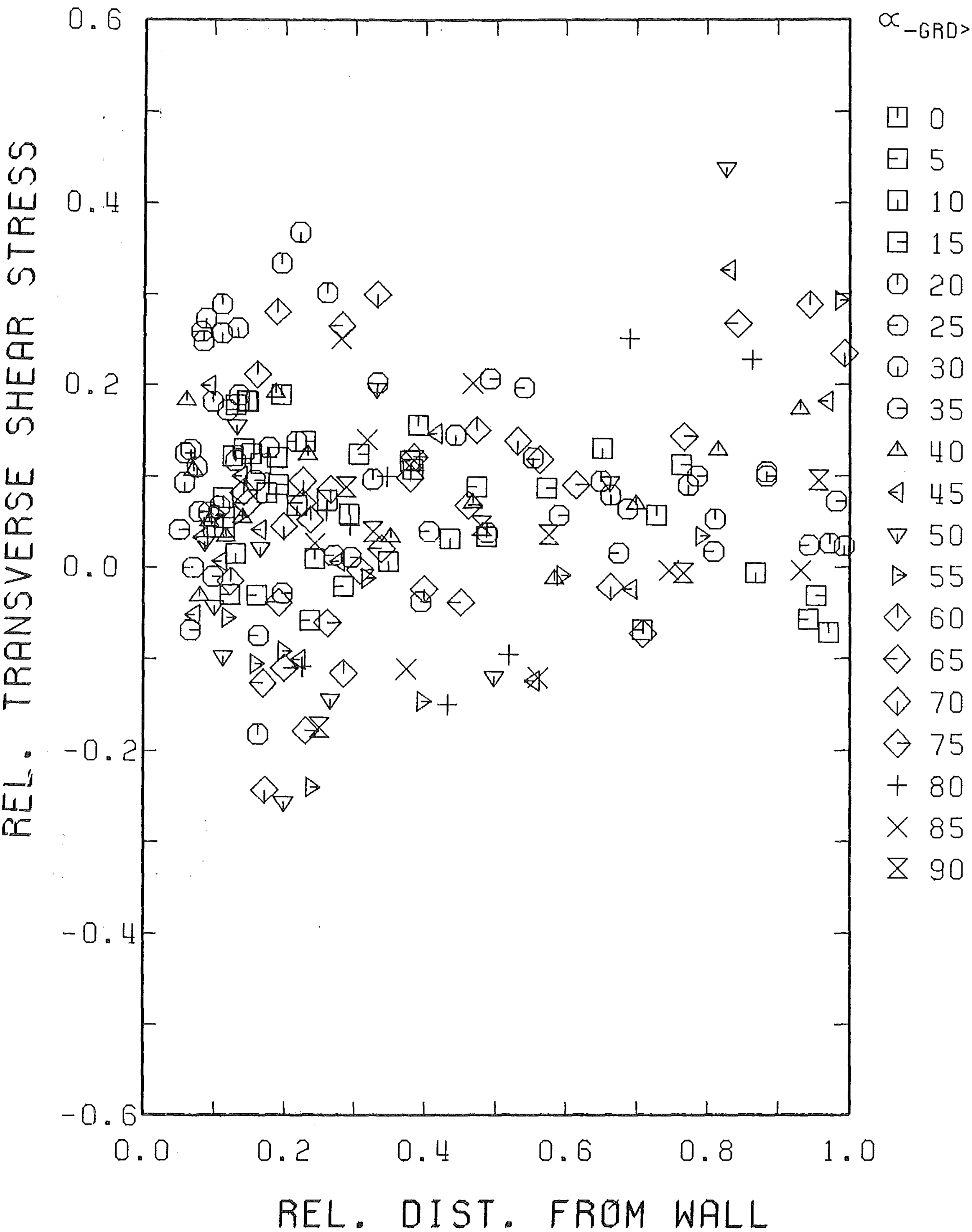


Fig. 27-4 Distribution of transverse shear stress
in the r/ϕ-part of quadrant 4

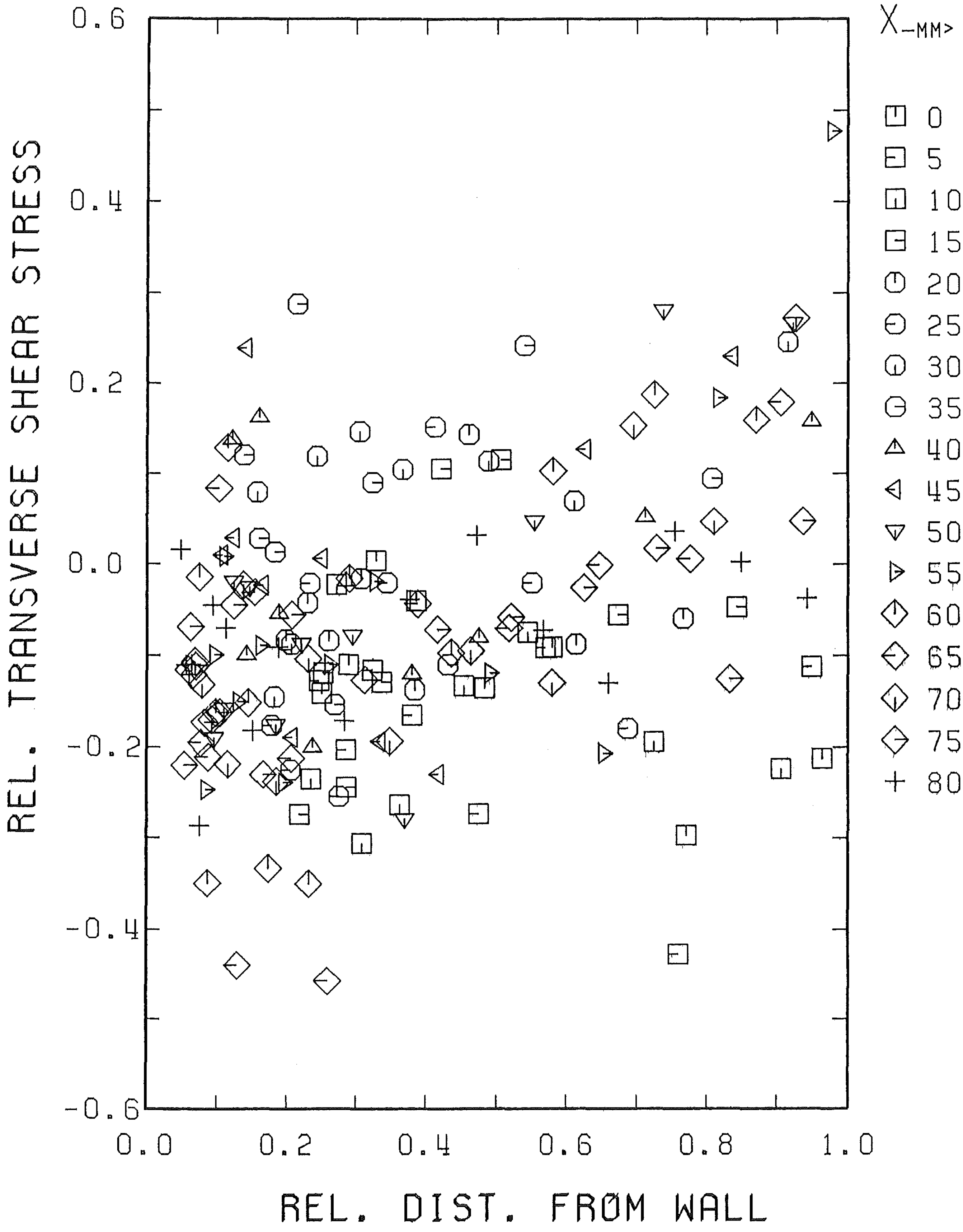


Fig. 28-1 Distribution of transverse shear stress in the x/y-part of quadrant 1

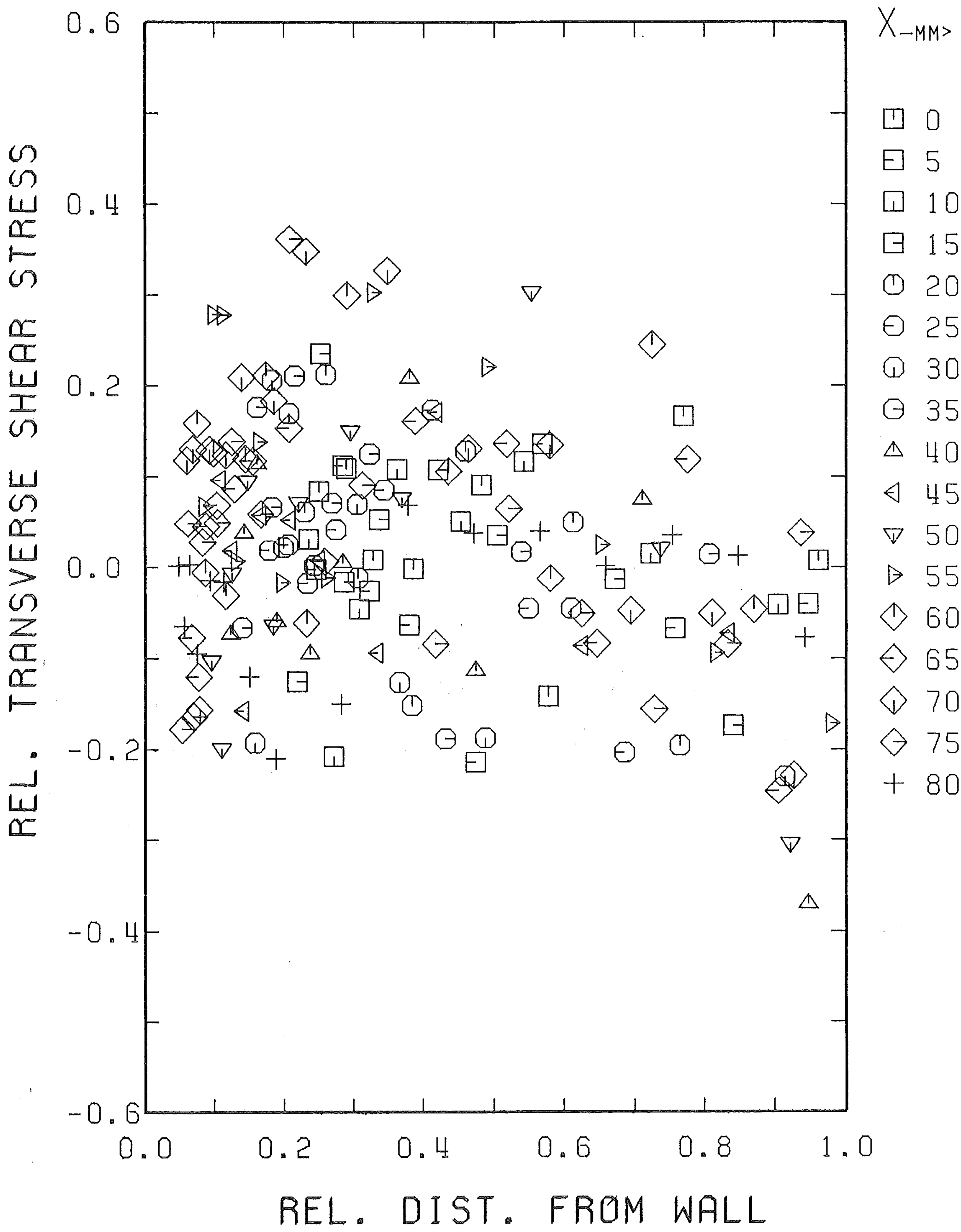


Fig. 28-2 Distribution of transverse shear stress
in the x/y-part of quadrant 2

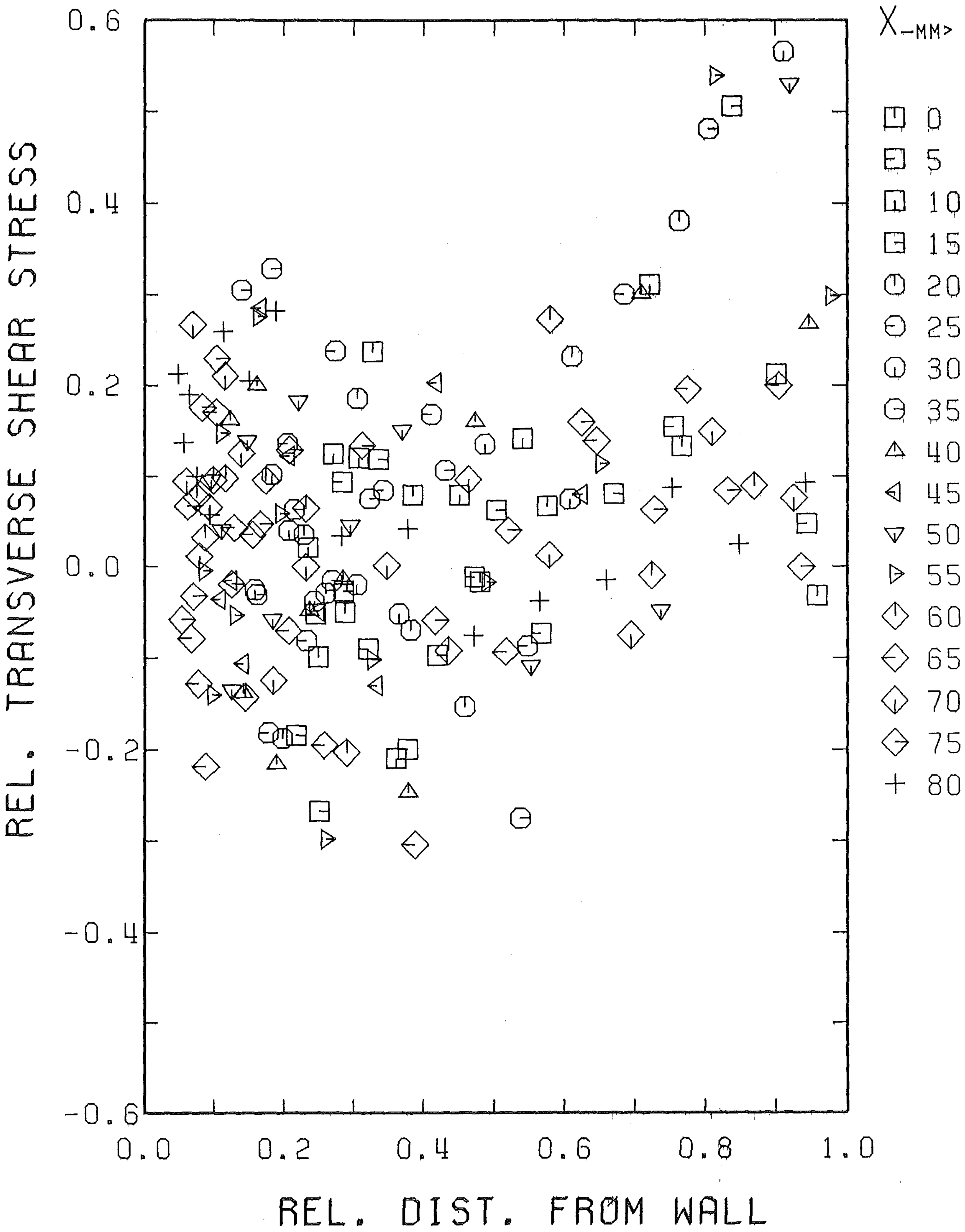


Fig. 28-3 Distribution of transverse shear stress
in the x/y-part of quadrant 3

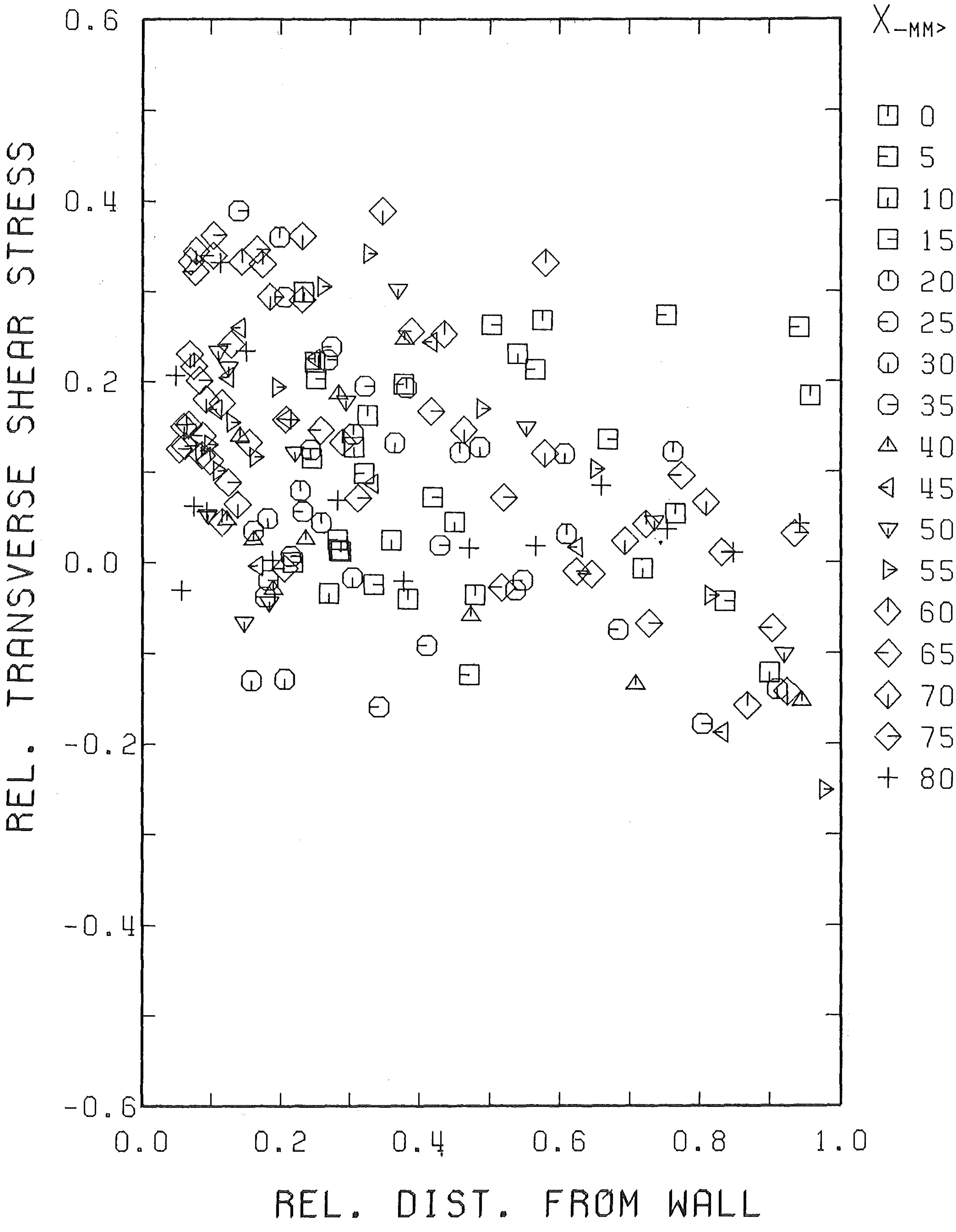


Fig. 28-4 Distribution of transverse shear stress
in the x/y-part of quadrant 4

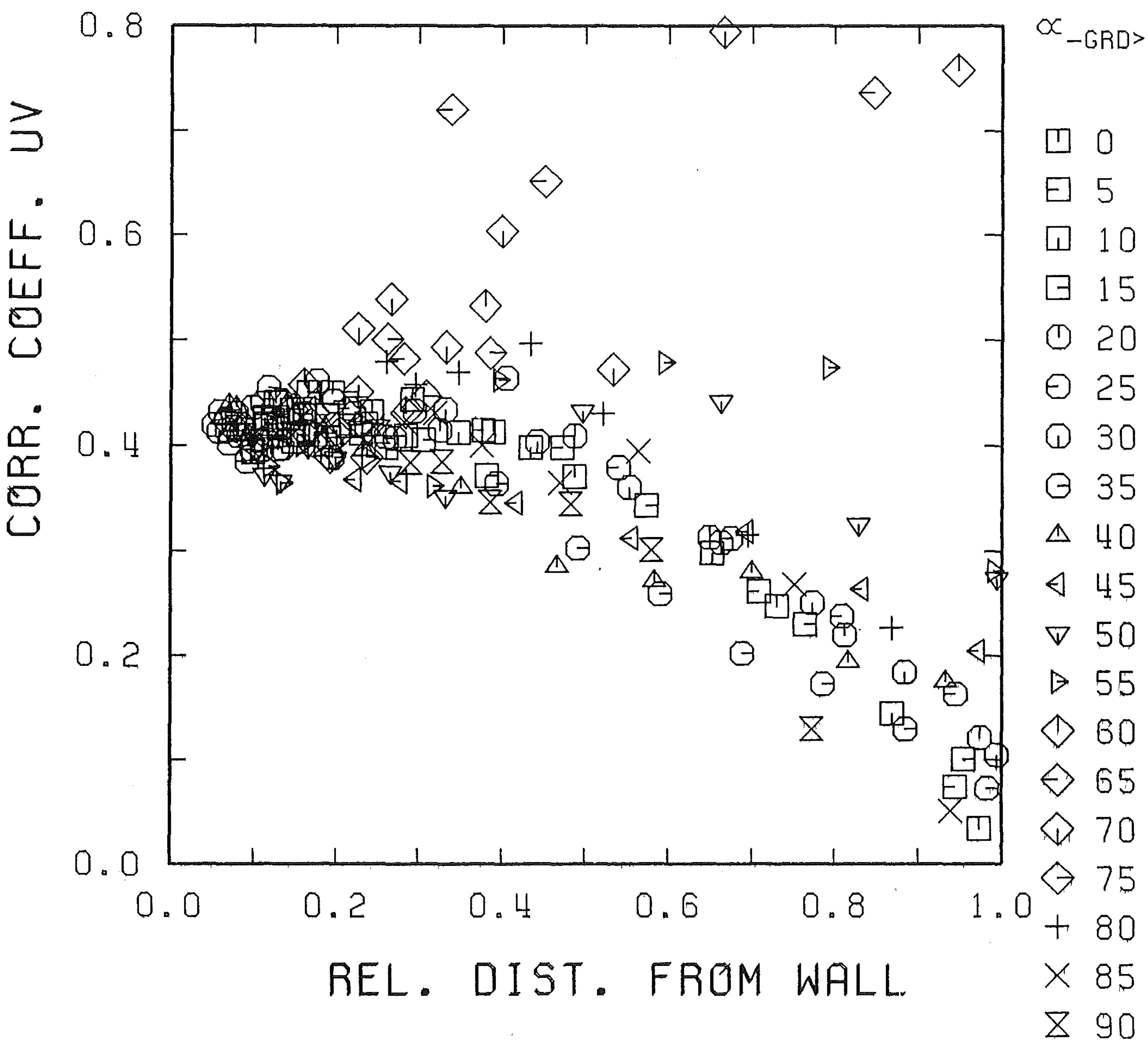


Fig. 29-1 Distribution of the correlation coefficient perpendicular to the wall in the r/ϕ-part of quadrant 1

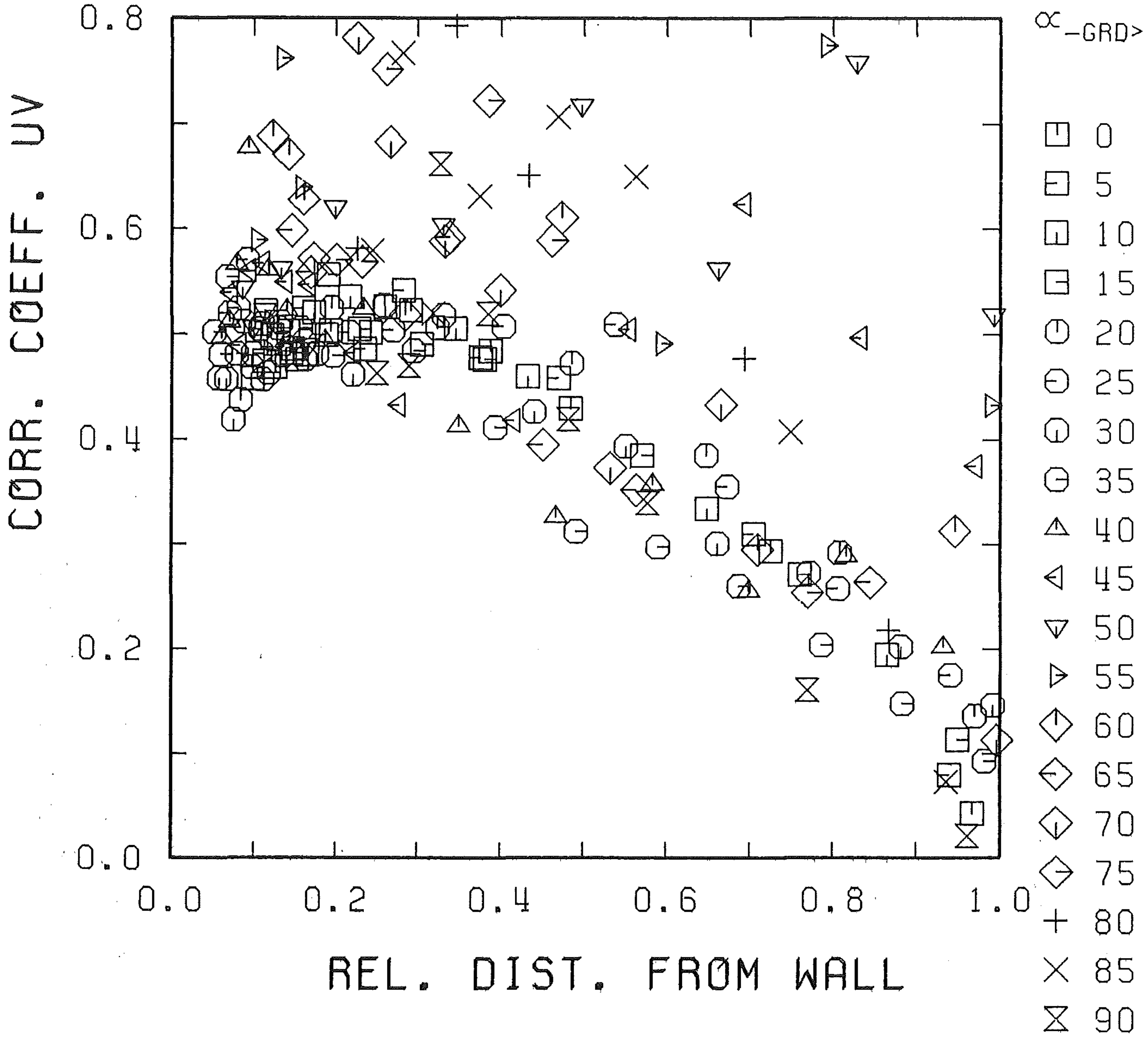


Fig. 29-2 Distribution of the correlation coefficient perpendicular to the wall in the r/ϕ-part of quadrant 2

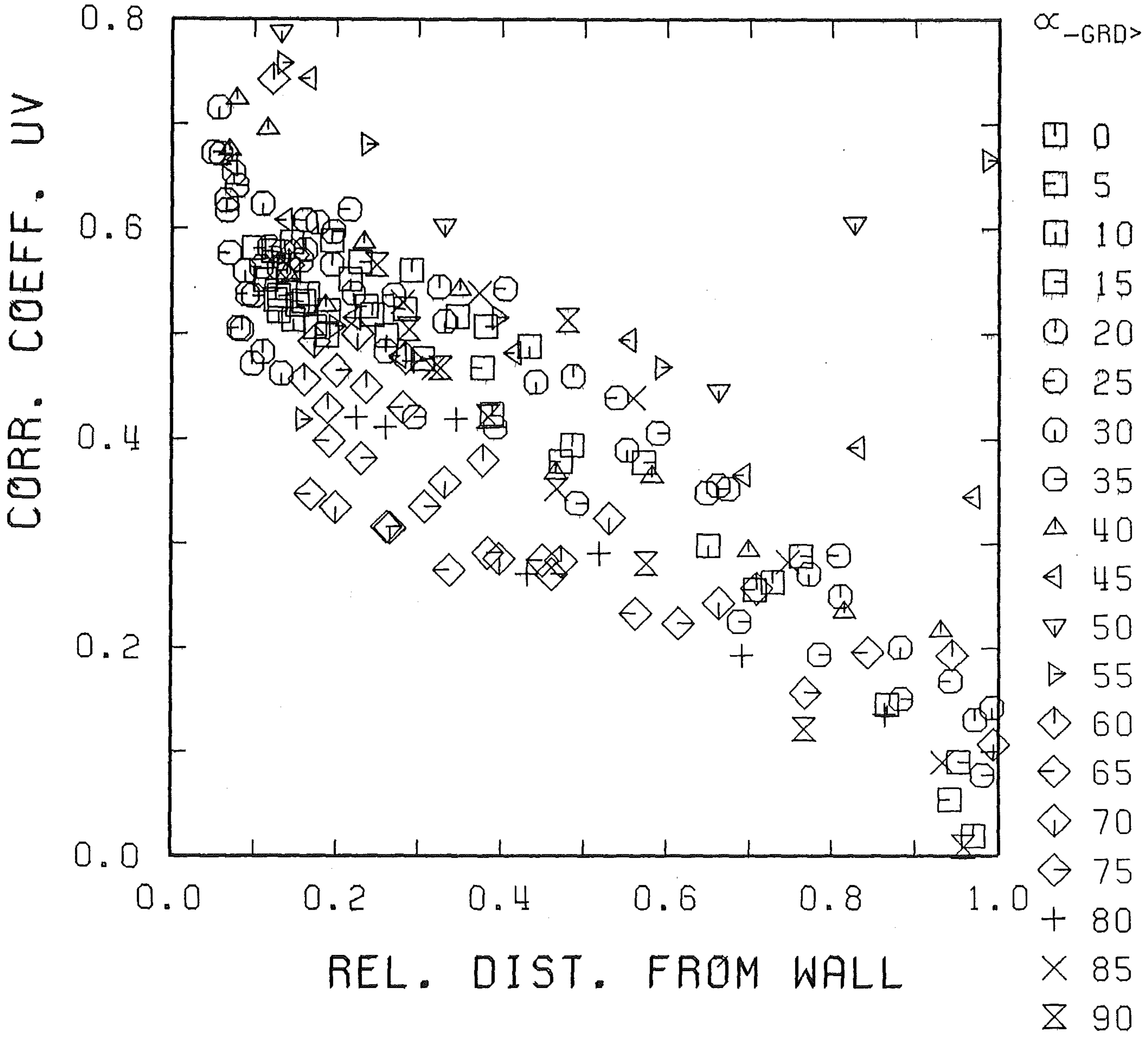


Fig. 29-3 Distribution of the correlation coefficient perpendicular to the wall in the r/ϕ-part of quadrant 3

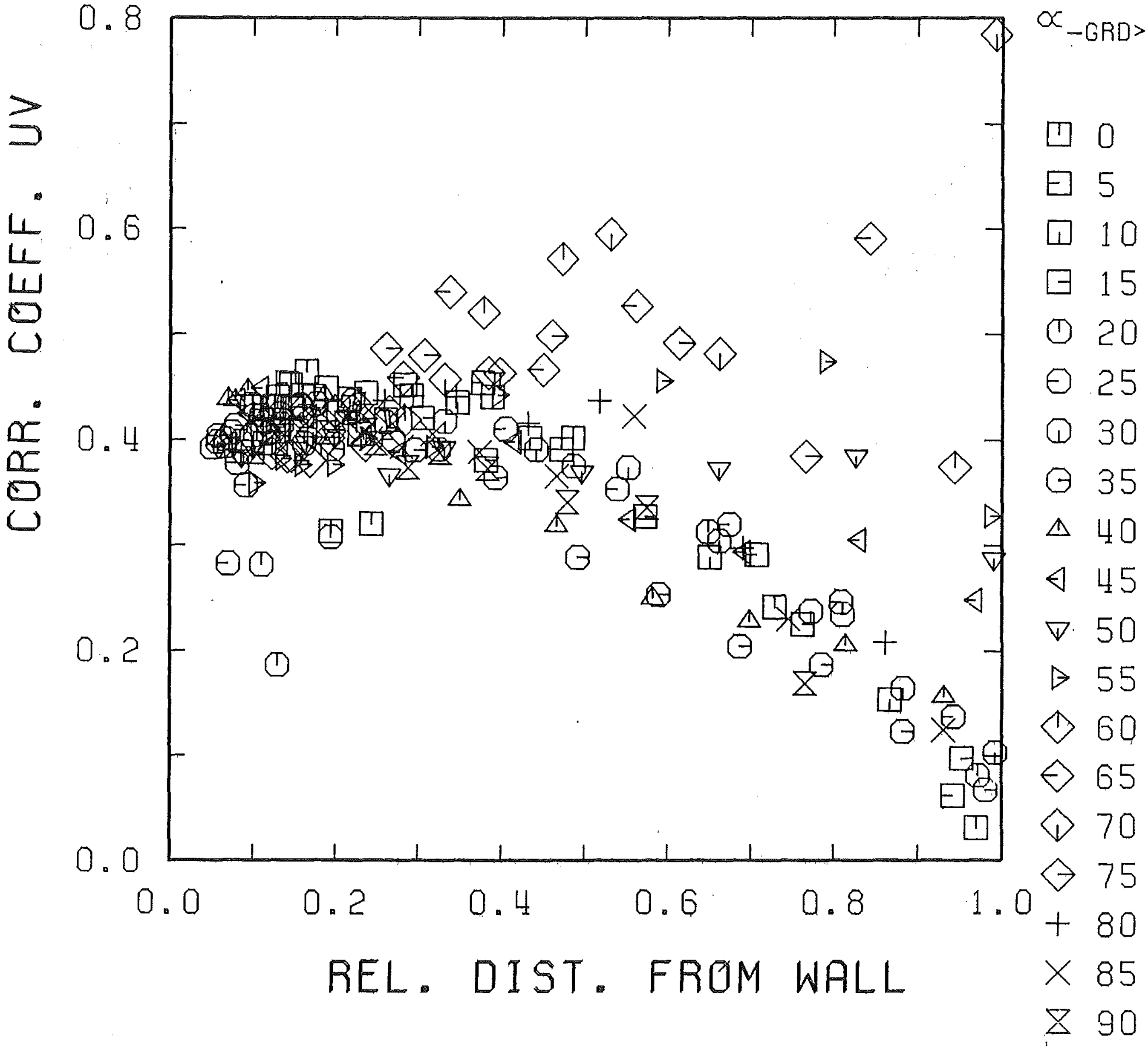


Fig. 29-4 Distribution of the correlation coefficient perpendicular to the wall in the r/ϕ-part of quadrant 4

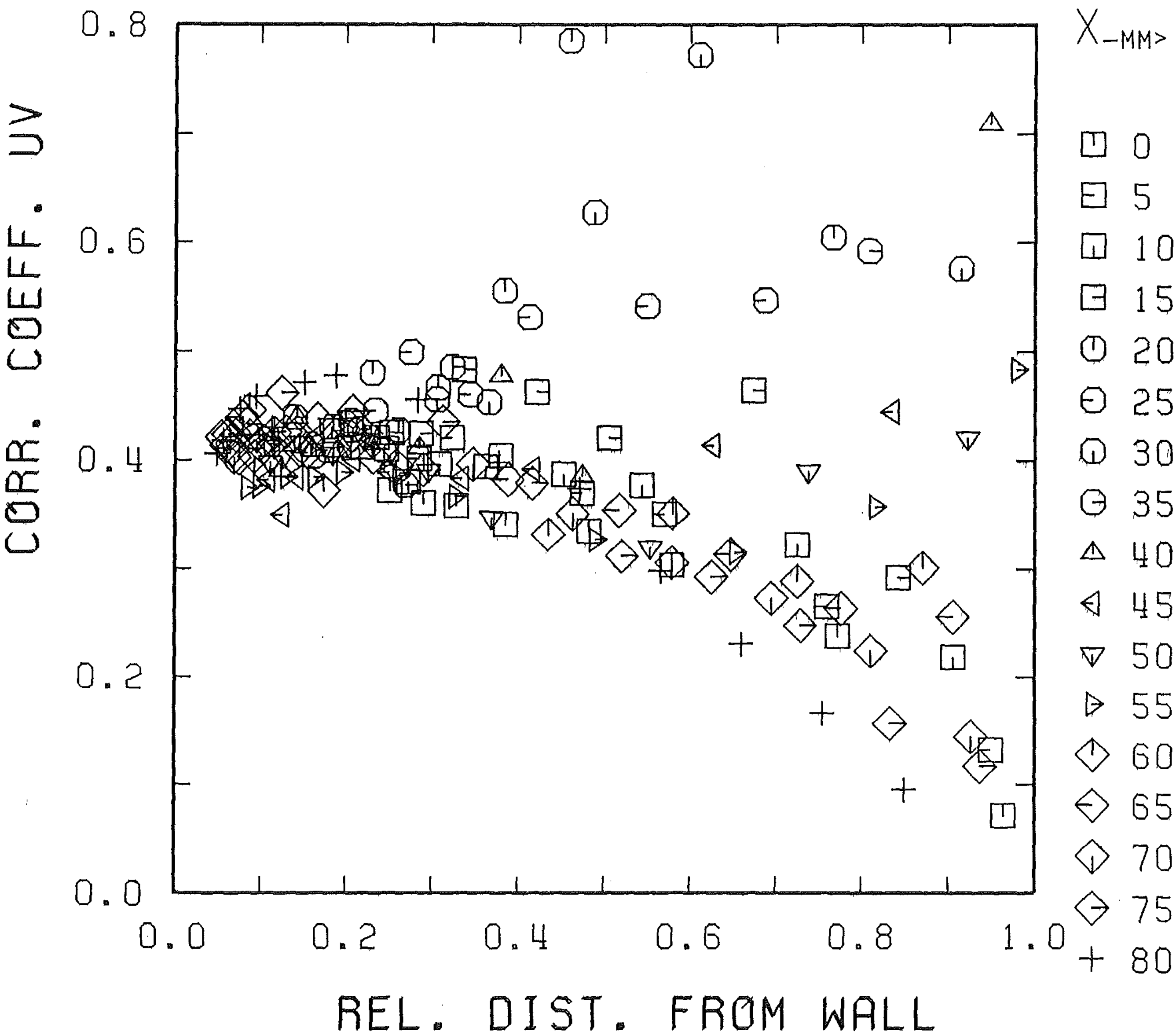


Fig. 30-1 Distribution of the correlation coefficient perpendicular to the wall in the x/y-part of quadrant 1

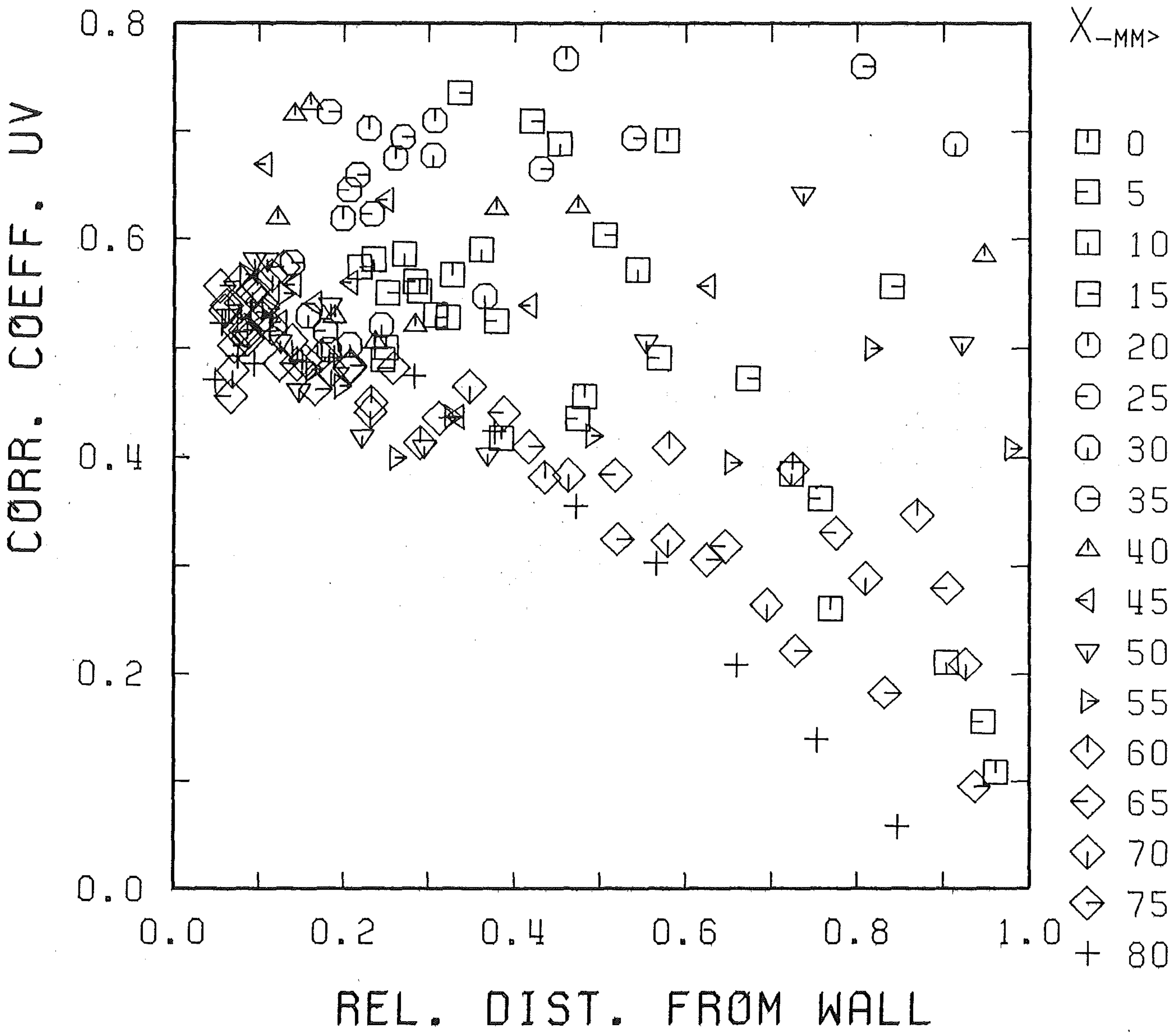


Fig. 30-2 Distribution of the correlation coefficient perpendicular to the wall in the x/y-part of quadrant 2

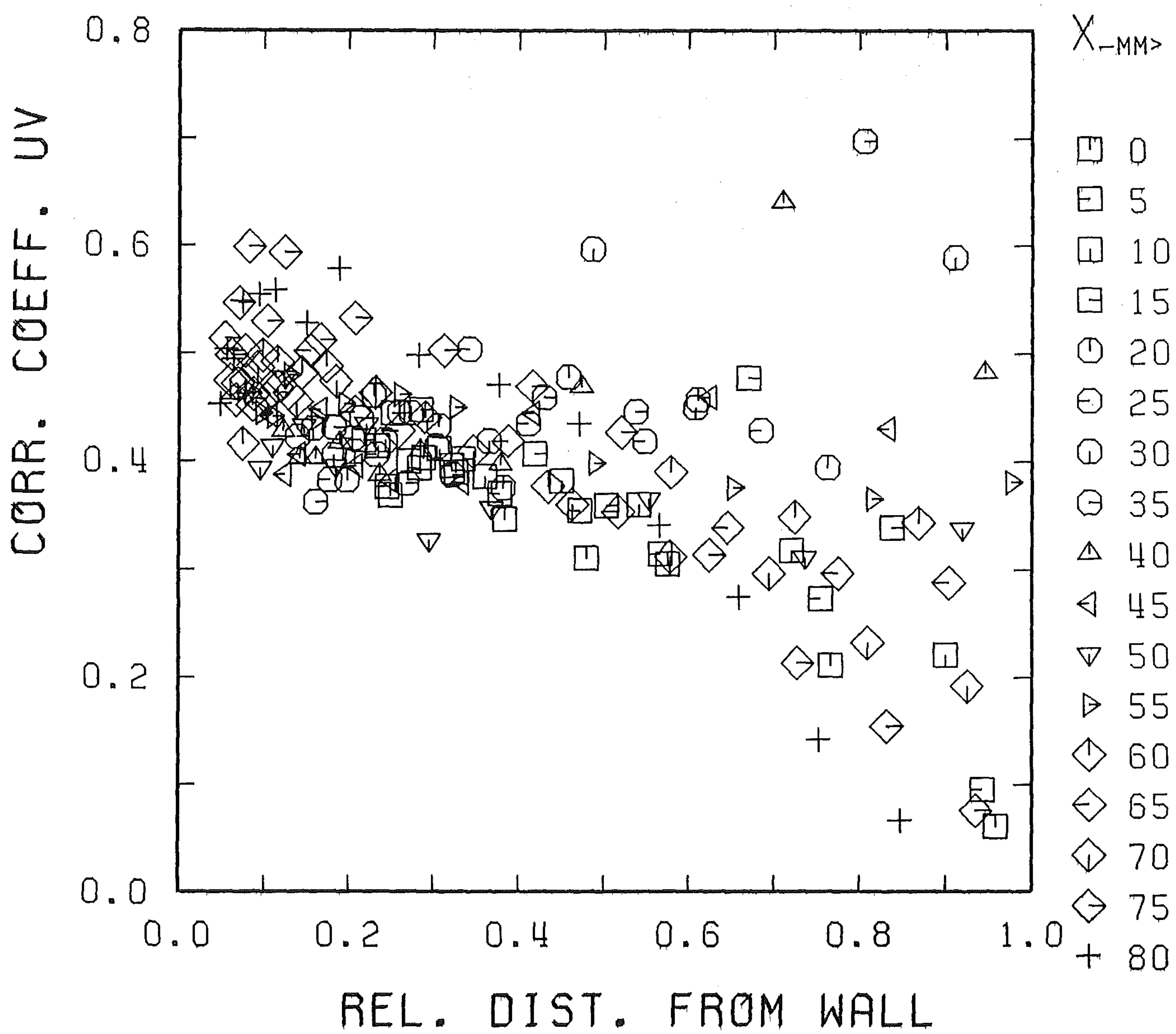


Fig. 30-3 Distribution of the correlation coefficient perpendicular to the wall in the x/y-part of quadrant 3

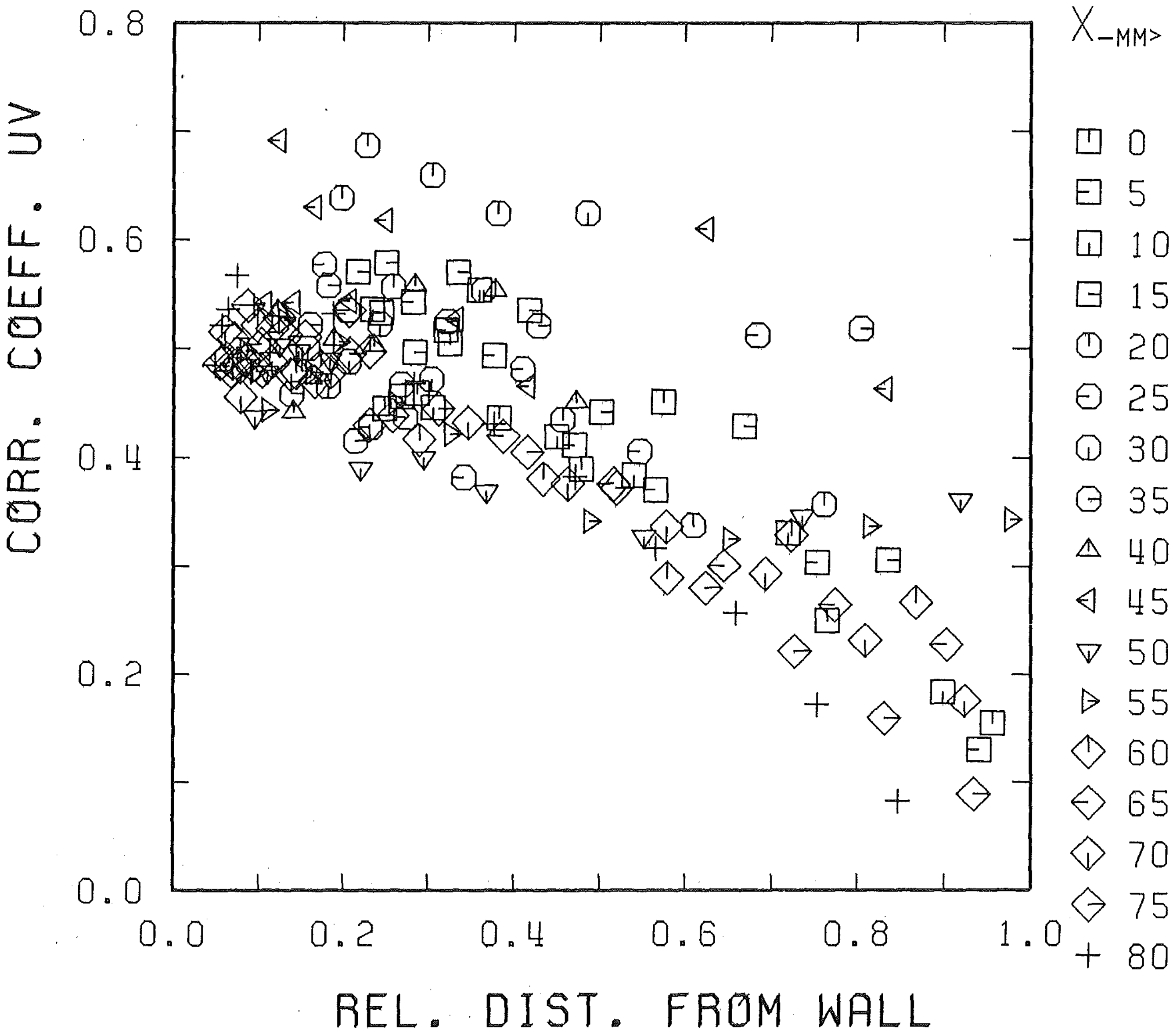


Fig. 30-4 Distribution of the correlation coefficient perpendicular to the wall in the x/y-part of quadrant 4

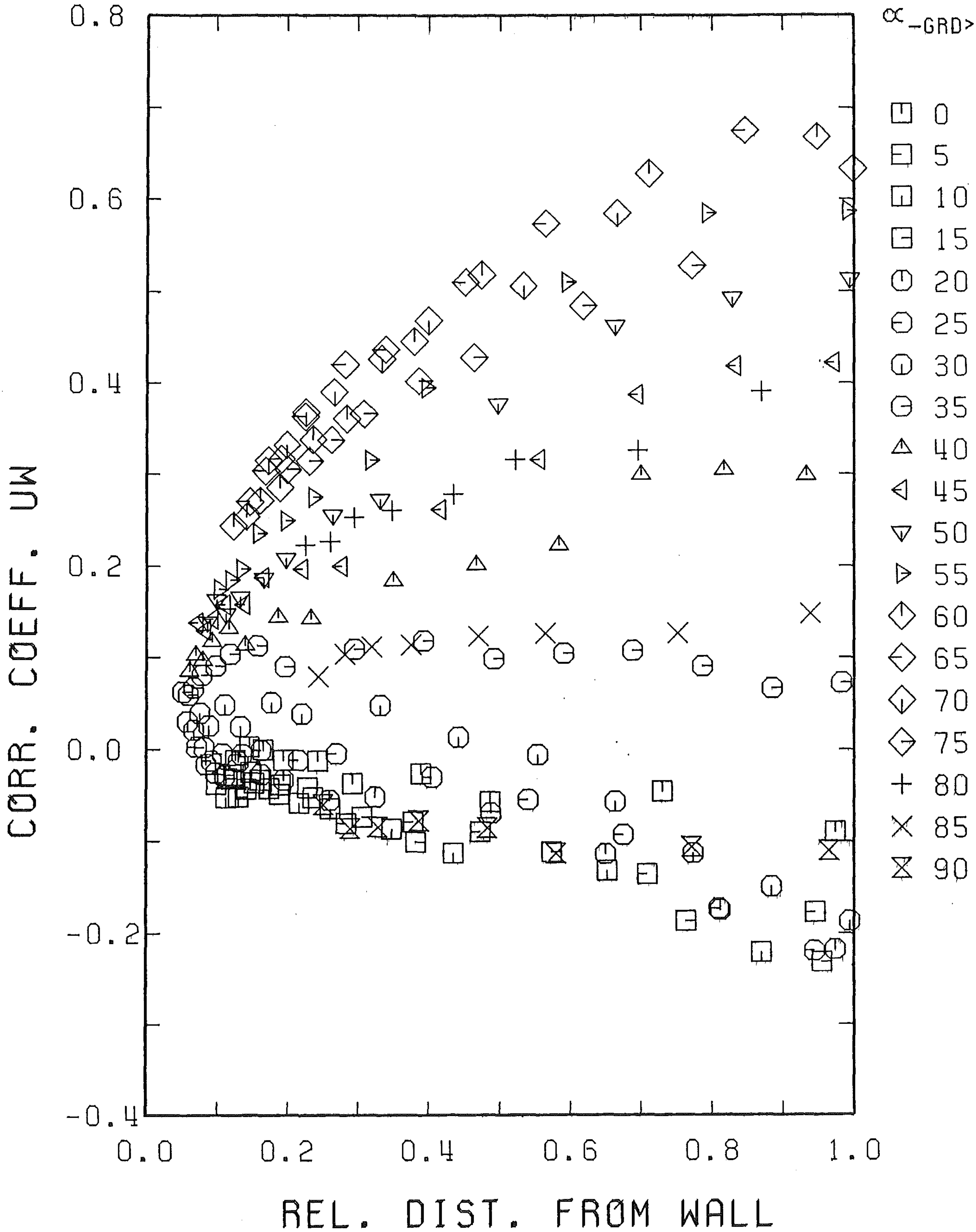


Fig. 31-1 Distribution of the correlation coefficient parallel to the wall in the r/ϕ-part of quadrant 1

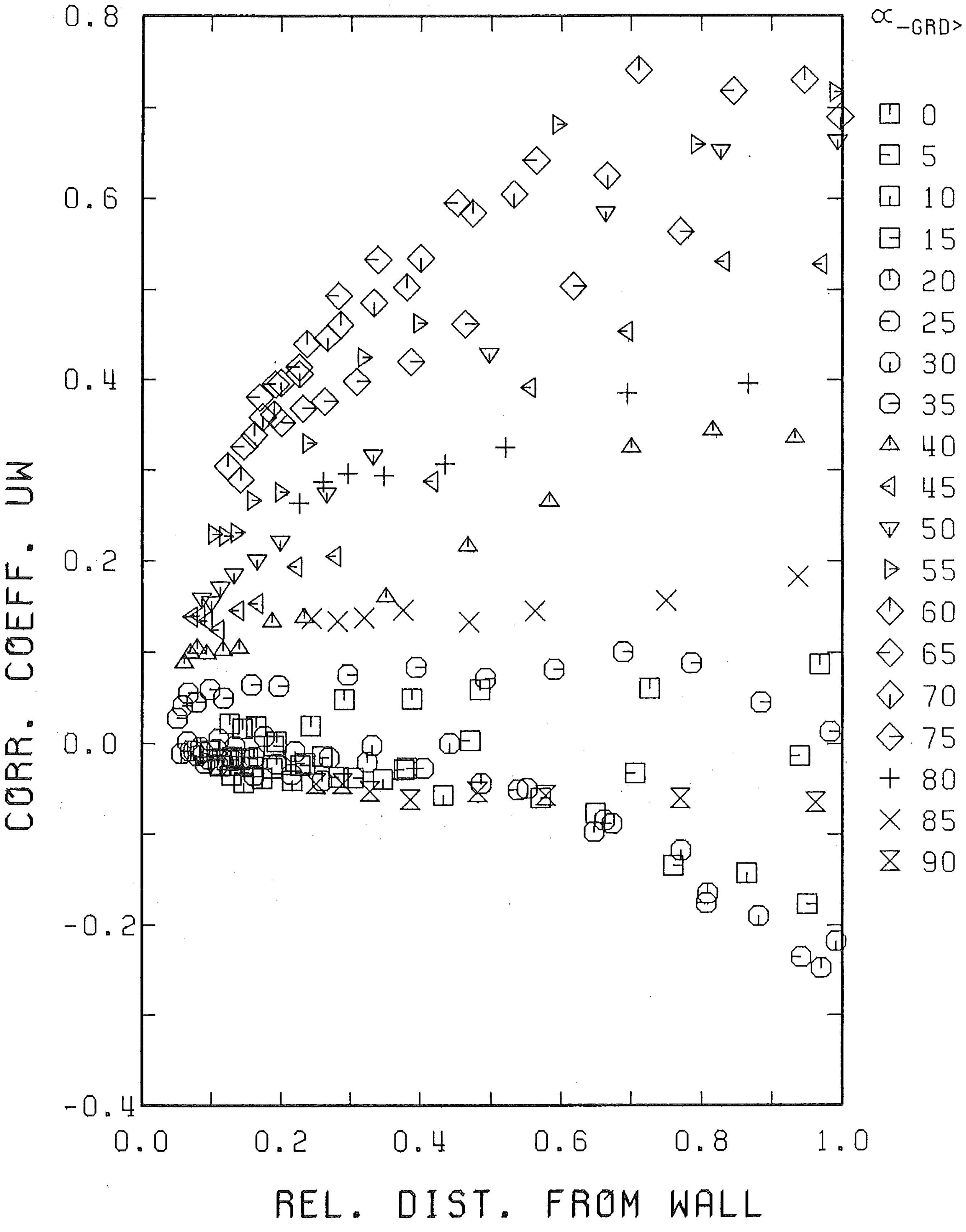


Fig. 31-2 Distribution of the correlation coefficient parallel to the wall in the r/ϕ-part of quadrant 2

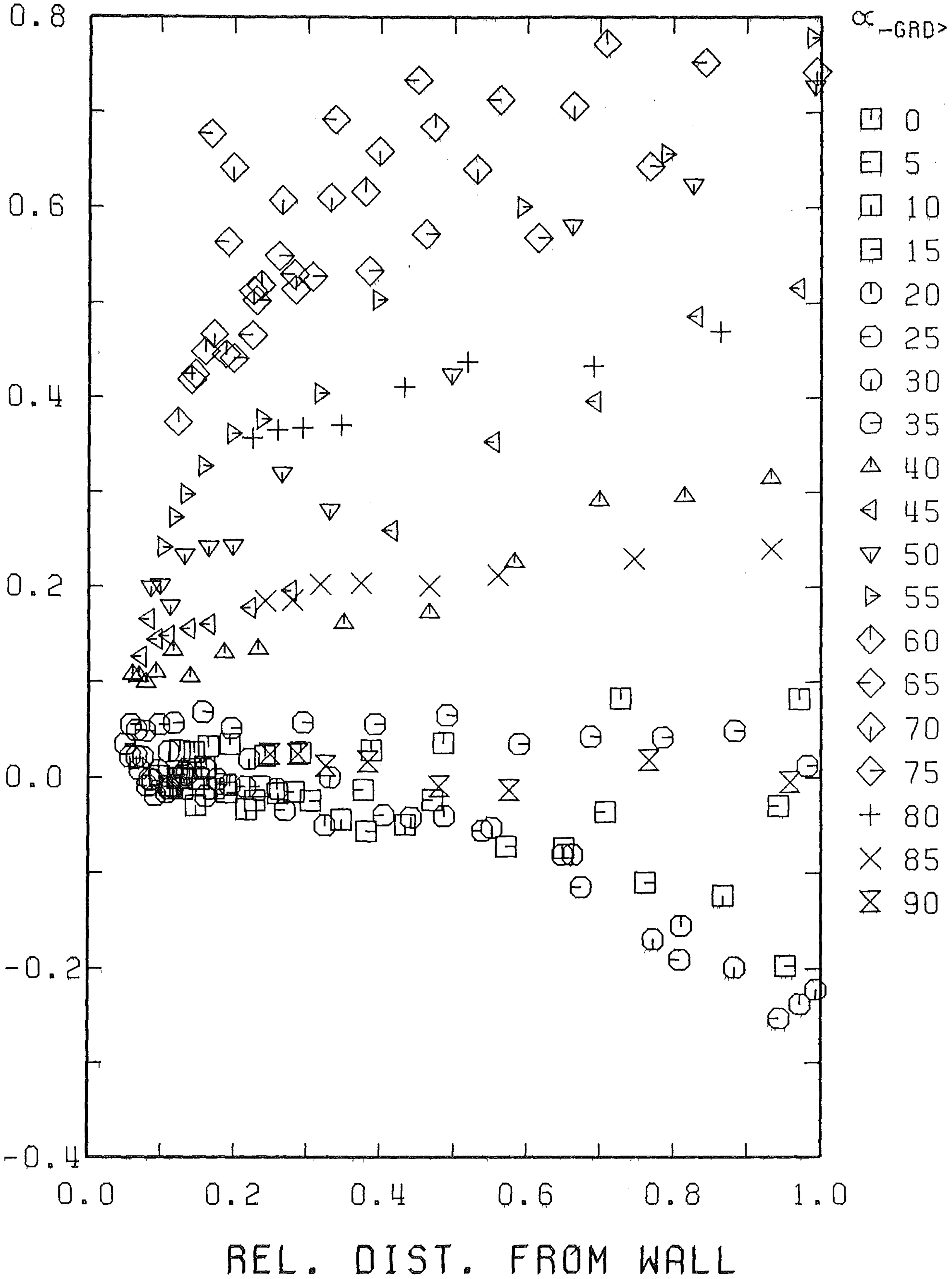


Fig. 31-3 Distribution of the correlation coefficient parallel to the wall in the r/φ-part of quadrant 3

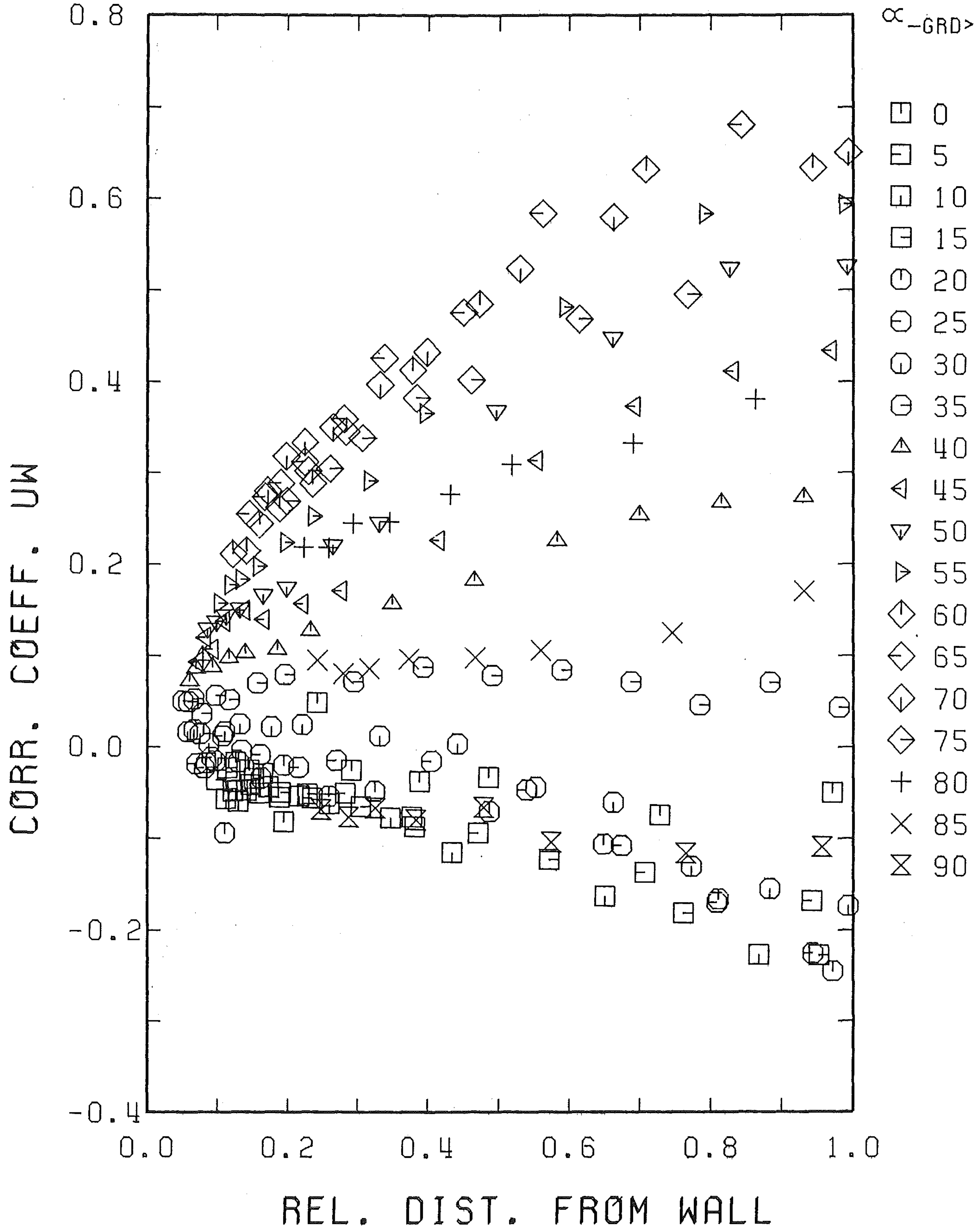


Fig. 31-4 Distribution of the correlation coefficient parallel to the wall in the r/ϕ-part of quadrant 4

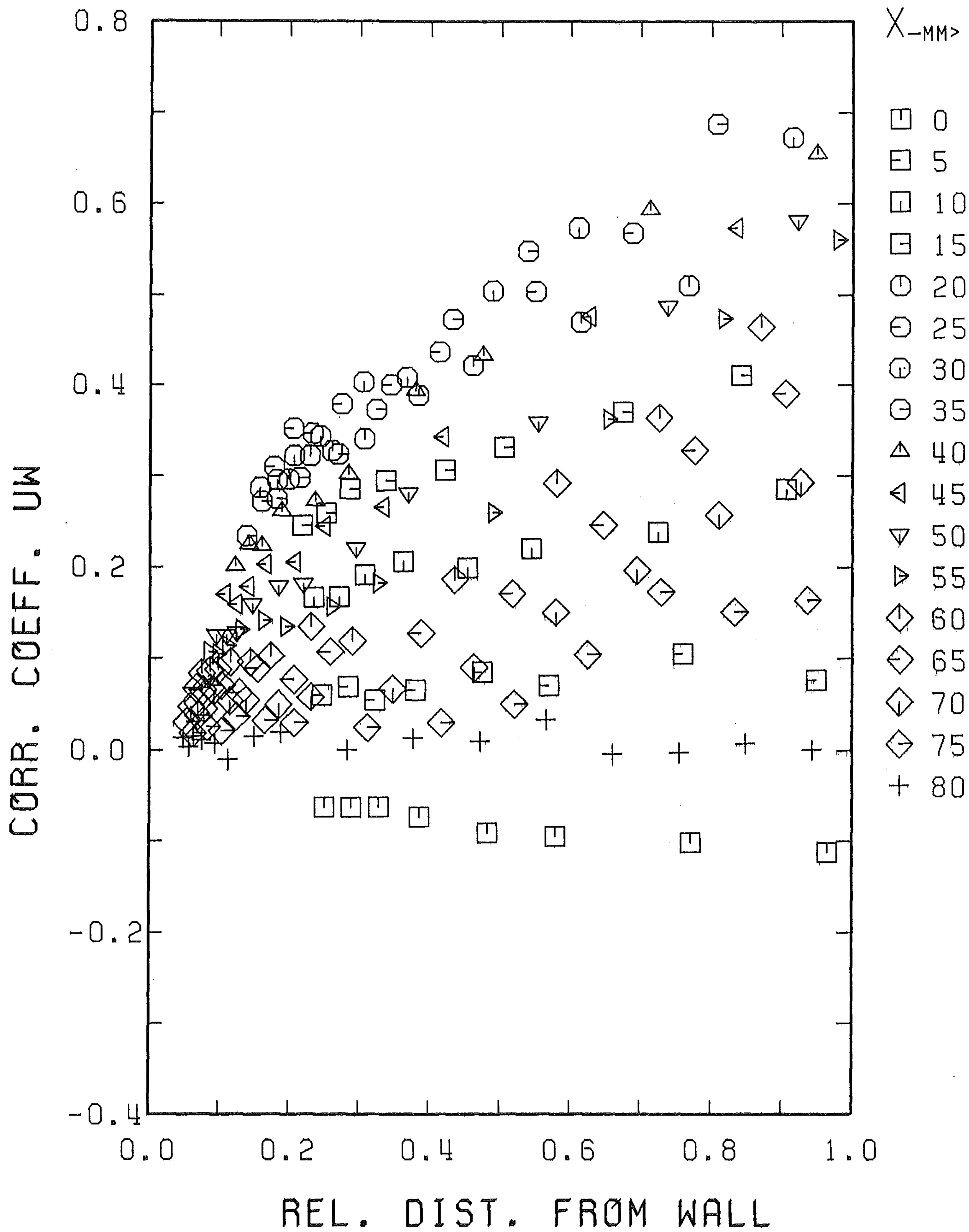


Fig. 32-1 Distribution of the correlation coefficient parallel to the wall in the x/y-part of quadrant 1

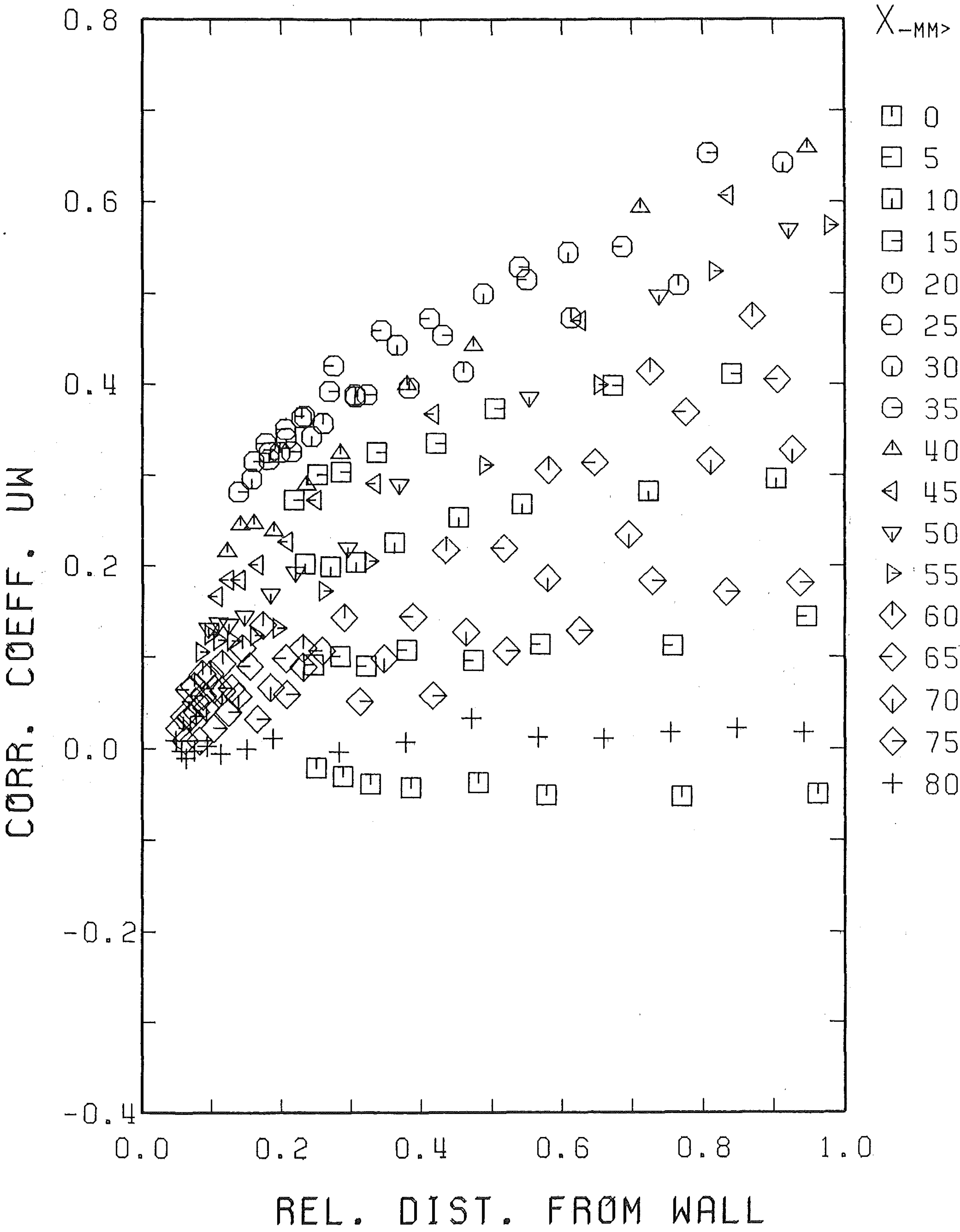


Fig. 32-2 Distribution of the correlation coefficient parallel to the wall in the x/y-part of quadrant 2

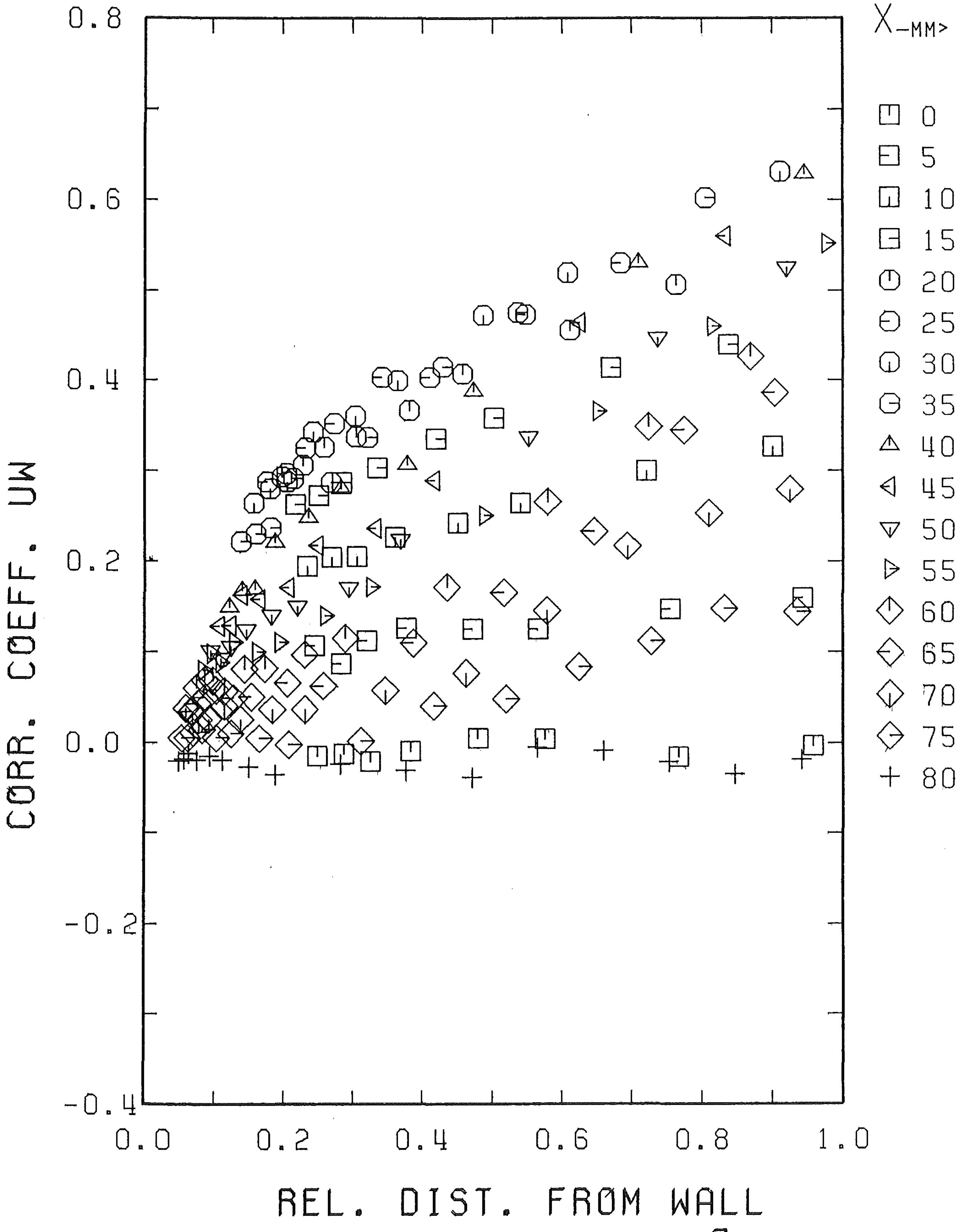


Fig. 32-3 Distribution of the correlation coefficient parallel to the wall in the x/y-part of quadrant 3

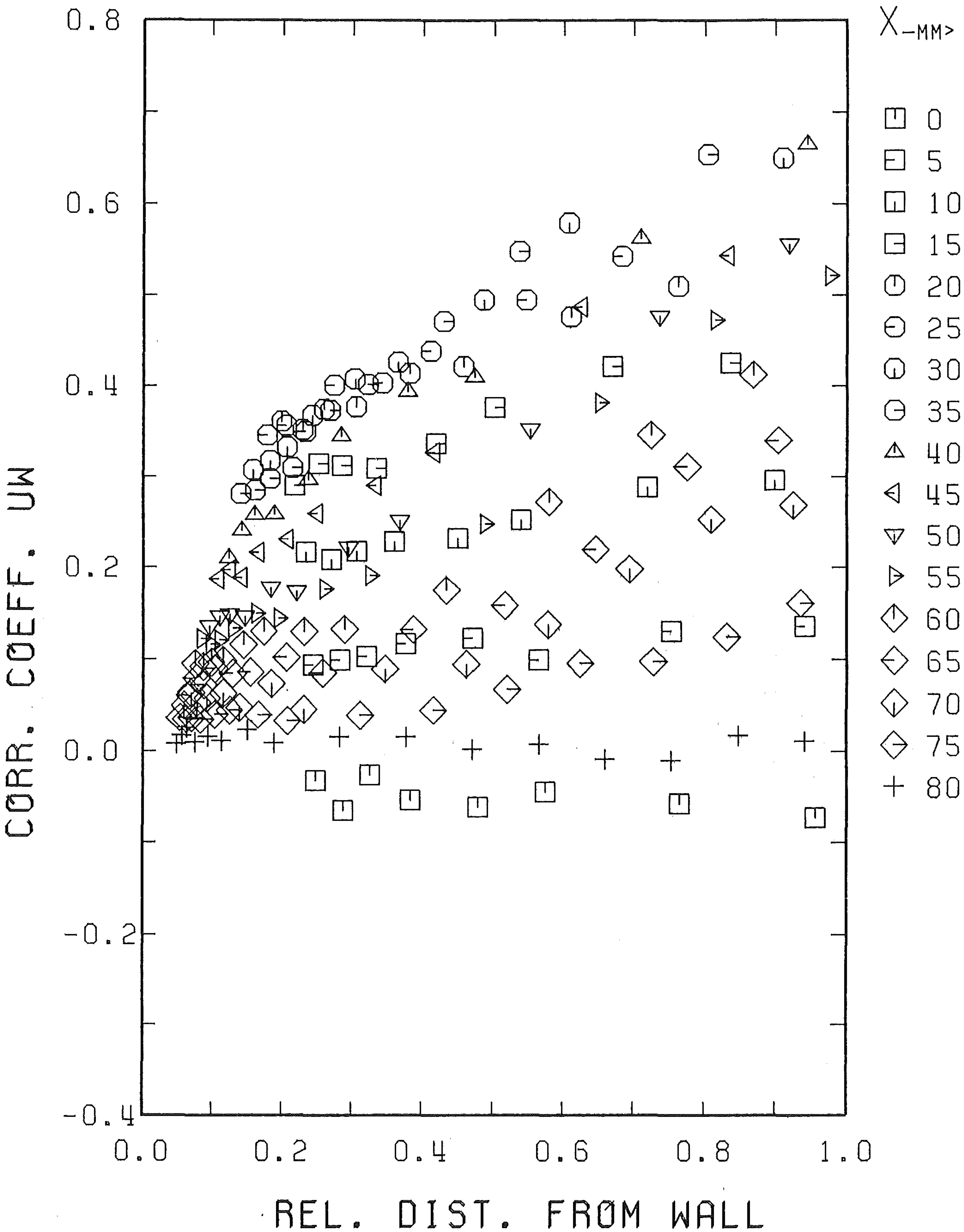


Fig. 32-4 Distribution of the correlation coefficient parallel to the wall in the x/y-part of quadrant 4

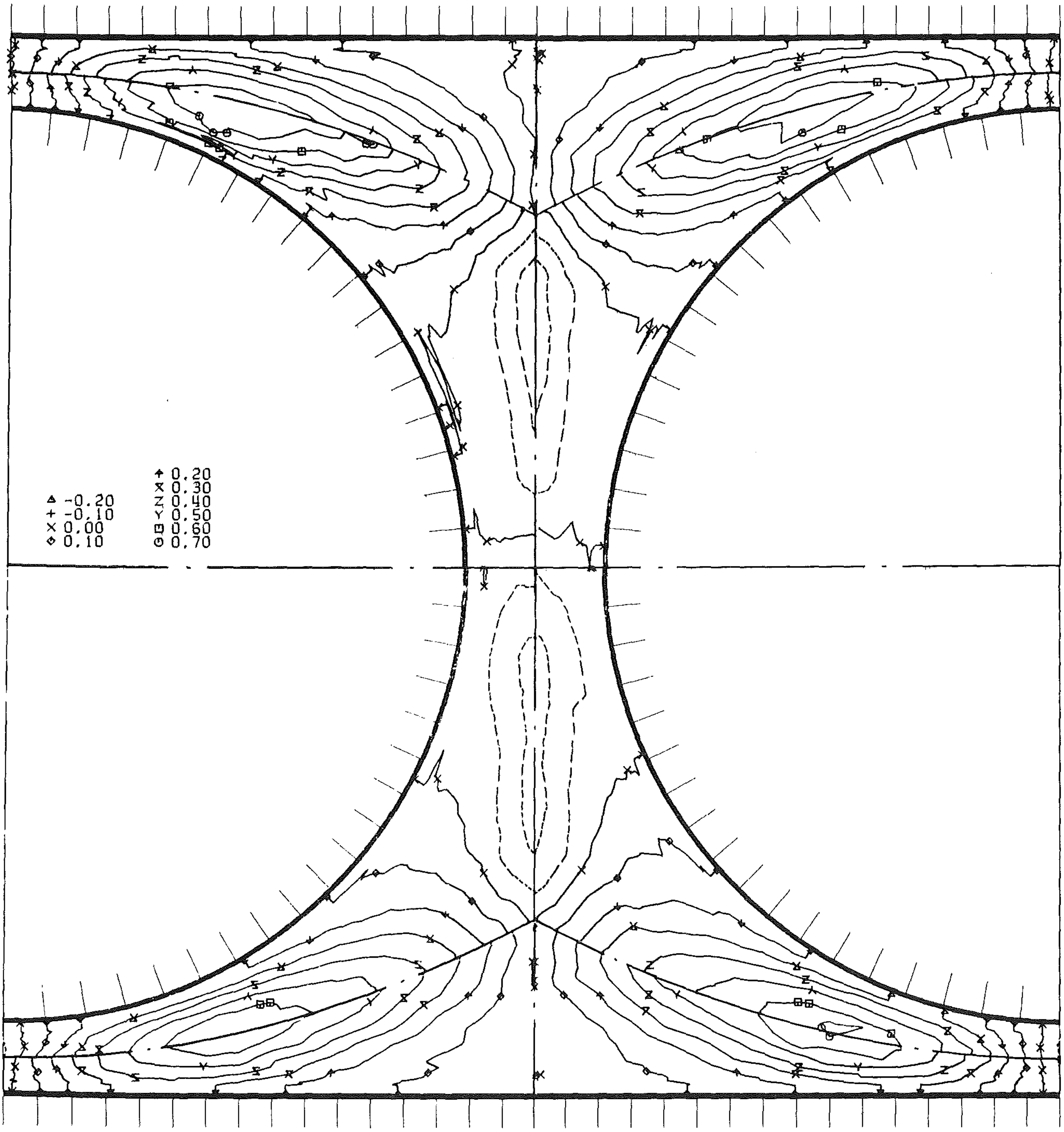


Fig. 33 Distribution of the correlation coefficient parallel to the wall in four quadrants

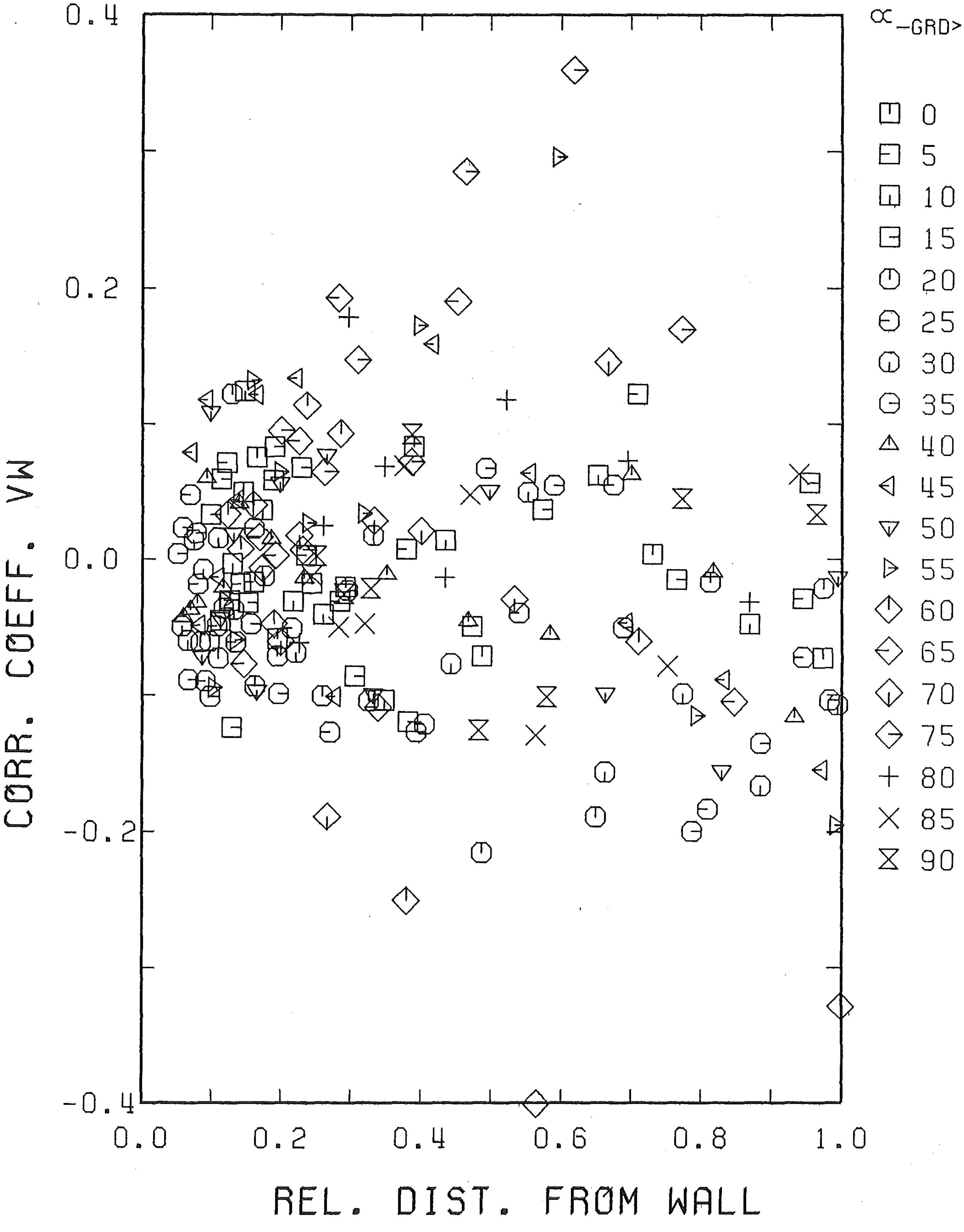


Fig. 34-1 Distribution of the correlation coefficient transverse to the wall in the r/ϕ-part of quadrant 1

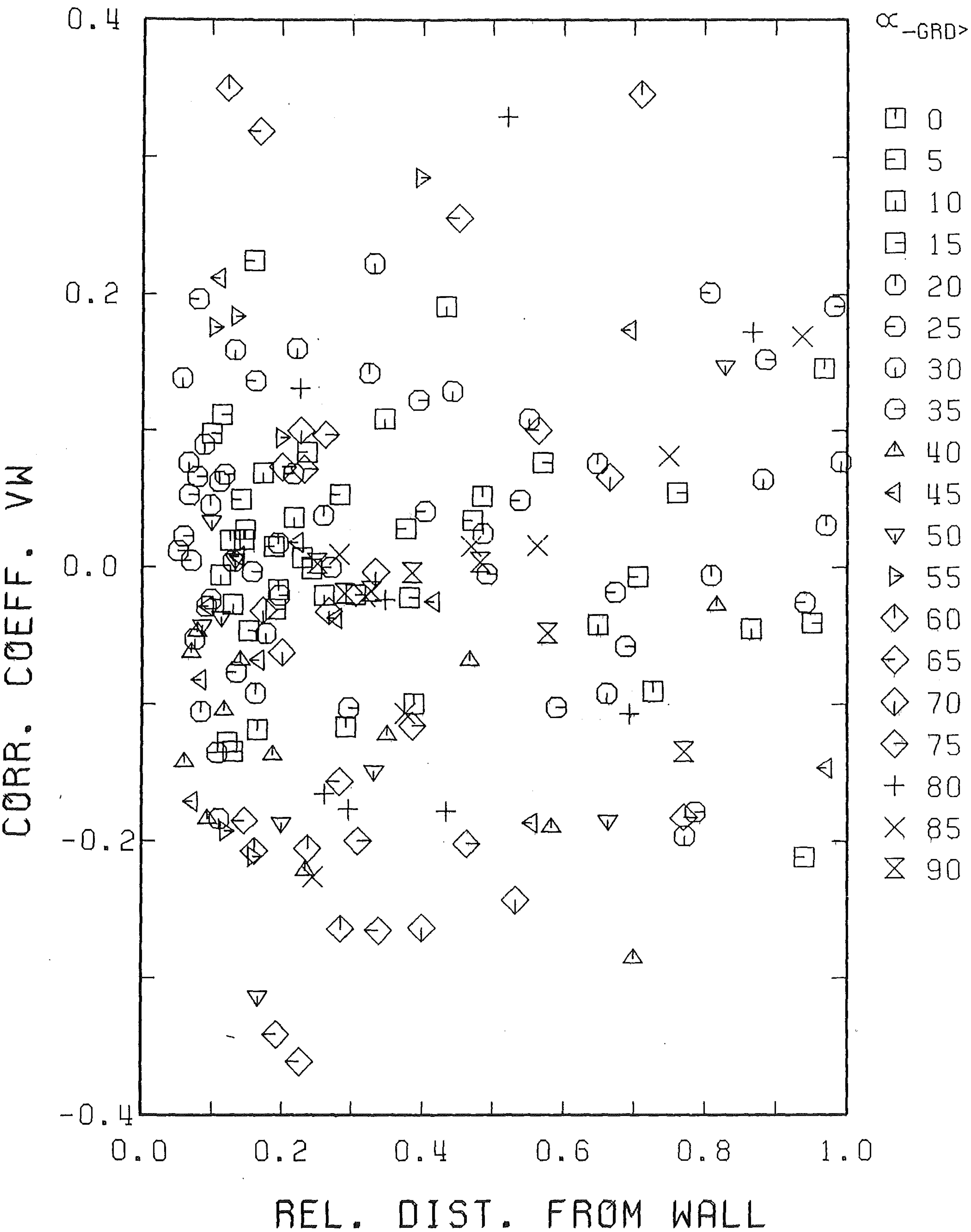


Fig. 34-2 Distribution of the correlation coefficient transverse to the wall in the r/ϕ-part of quadrant 2

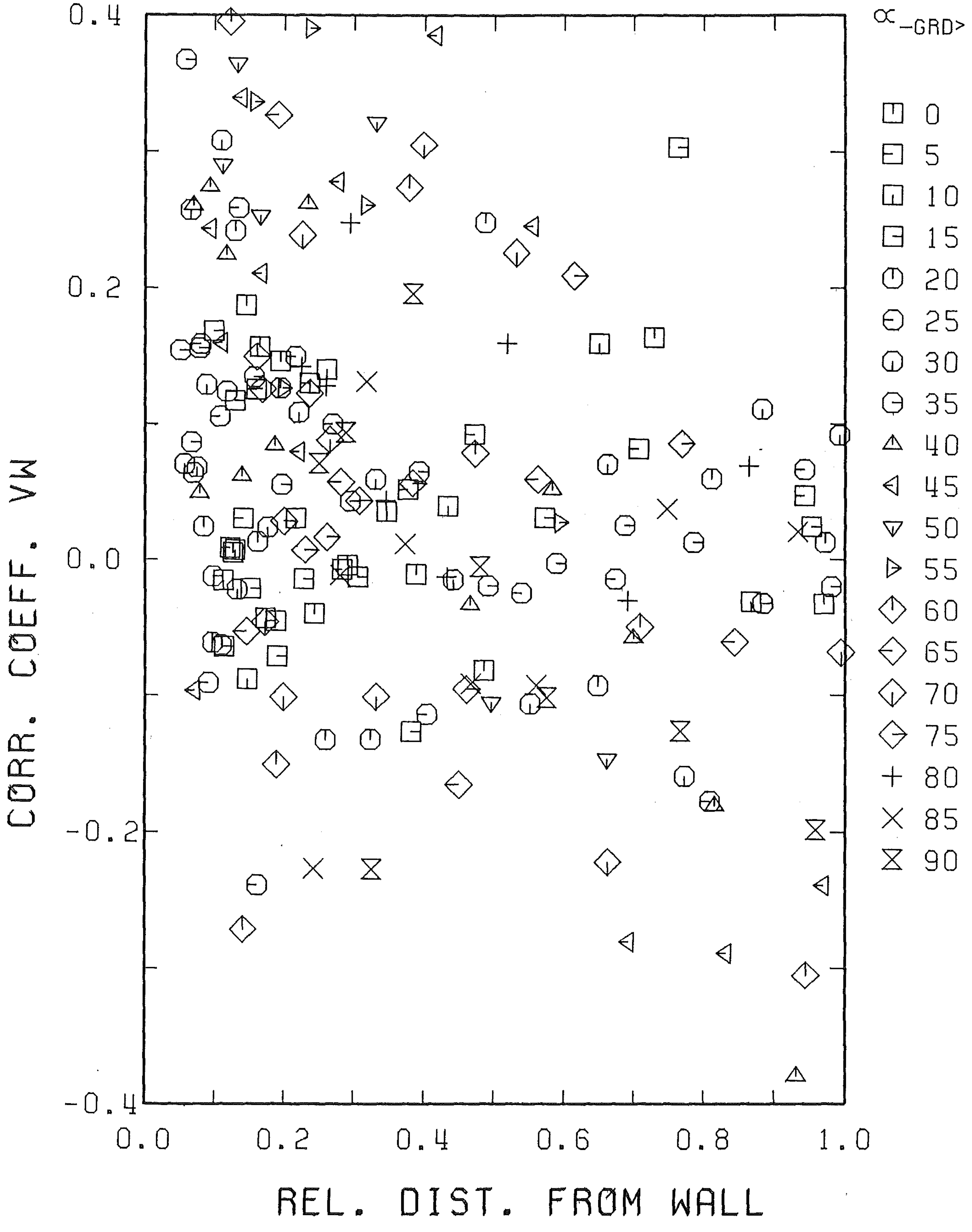


Fig. 34-3 Distribution of the correlation coefficient transverse to the wall in the r/ϕ-part of quadrant 3'

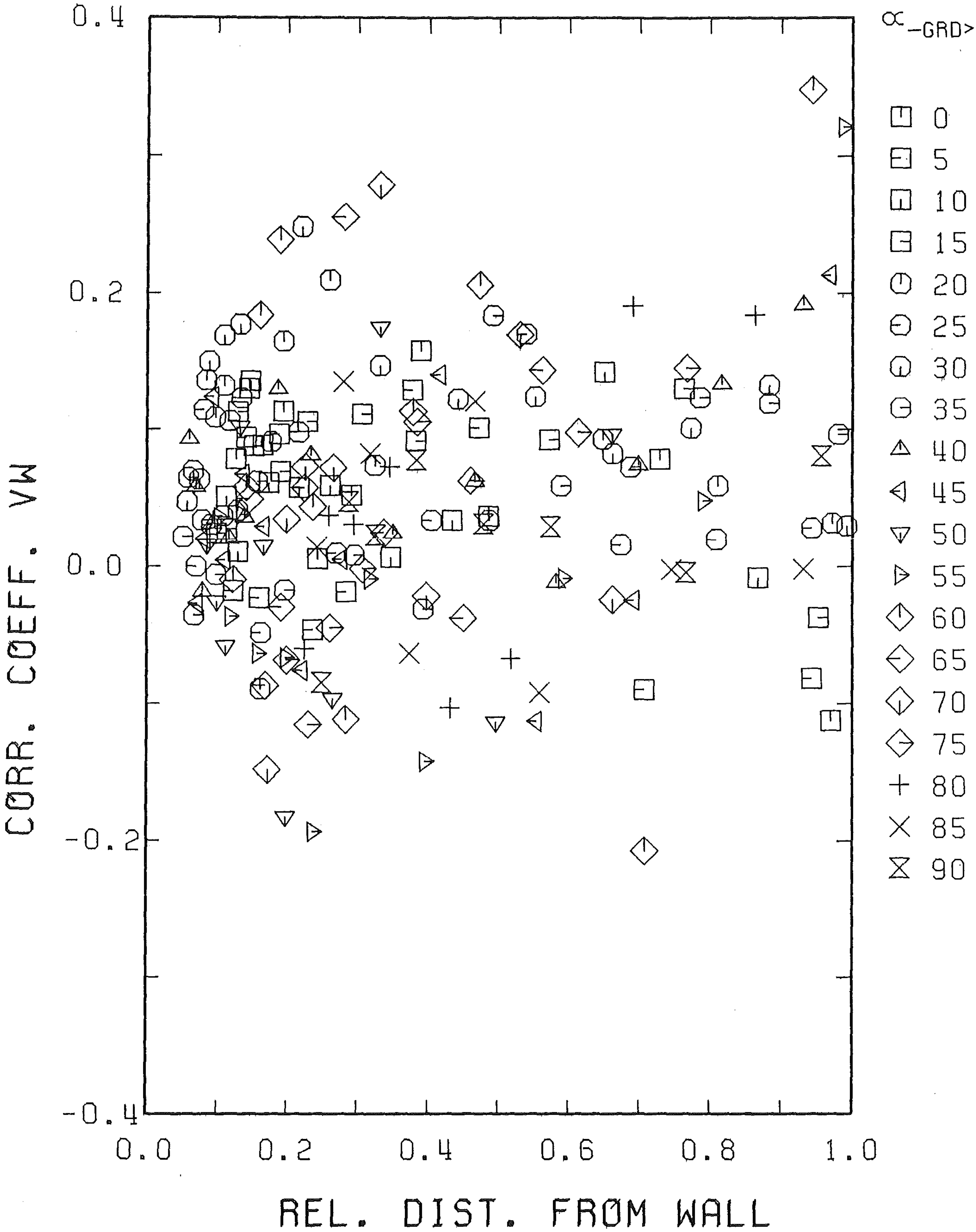


Fig. 34-4 Distribution of the correlation coefficient transverse to the wall in the r/ϕ-part of quadrant 4

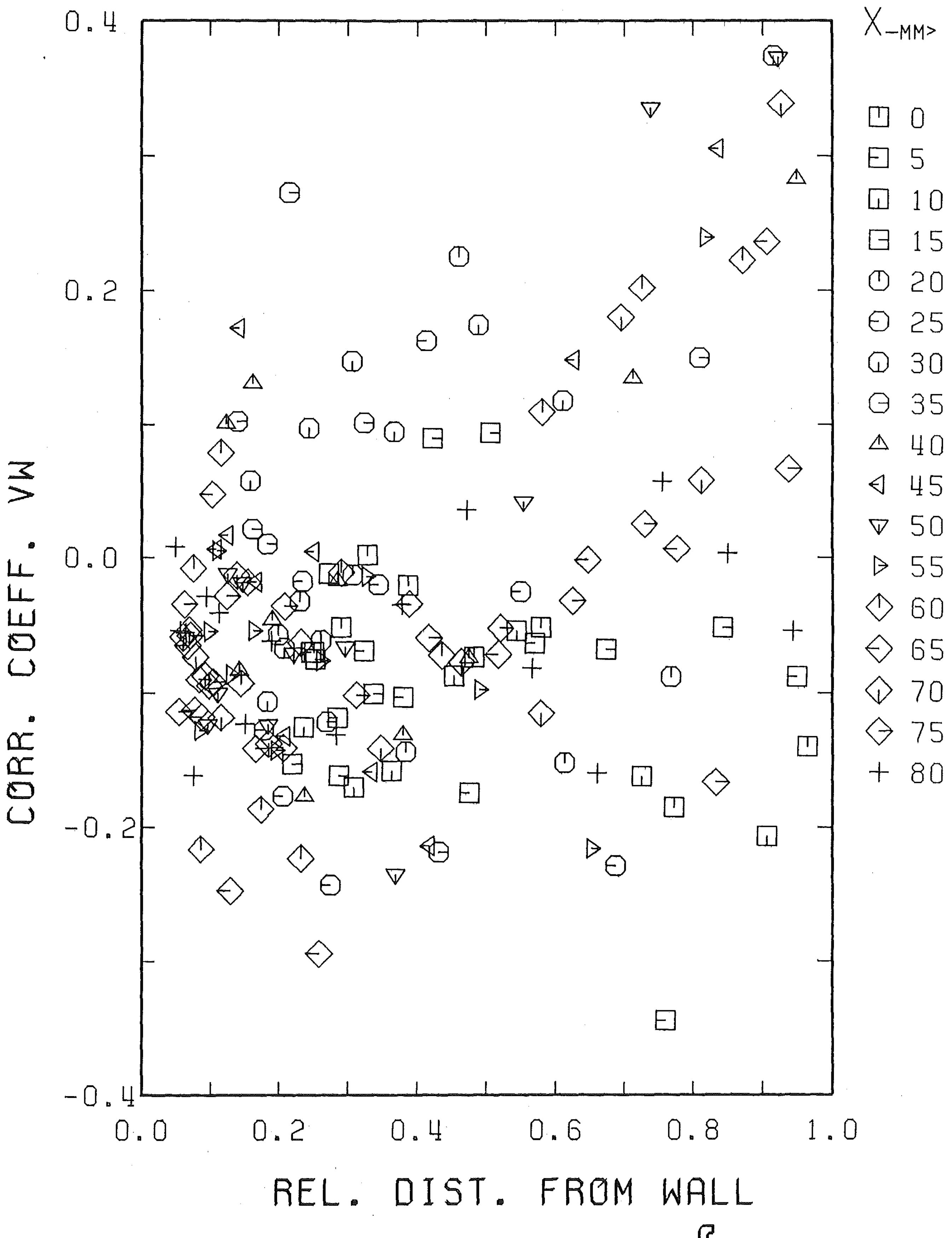


Fig. 35-1 Distribution of the correlation coefficient transverse to the wall in the x/y-part of quadrant 1

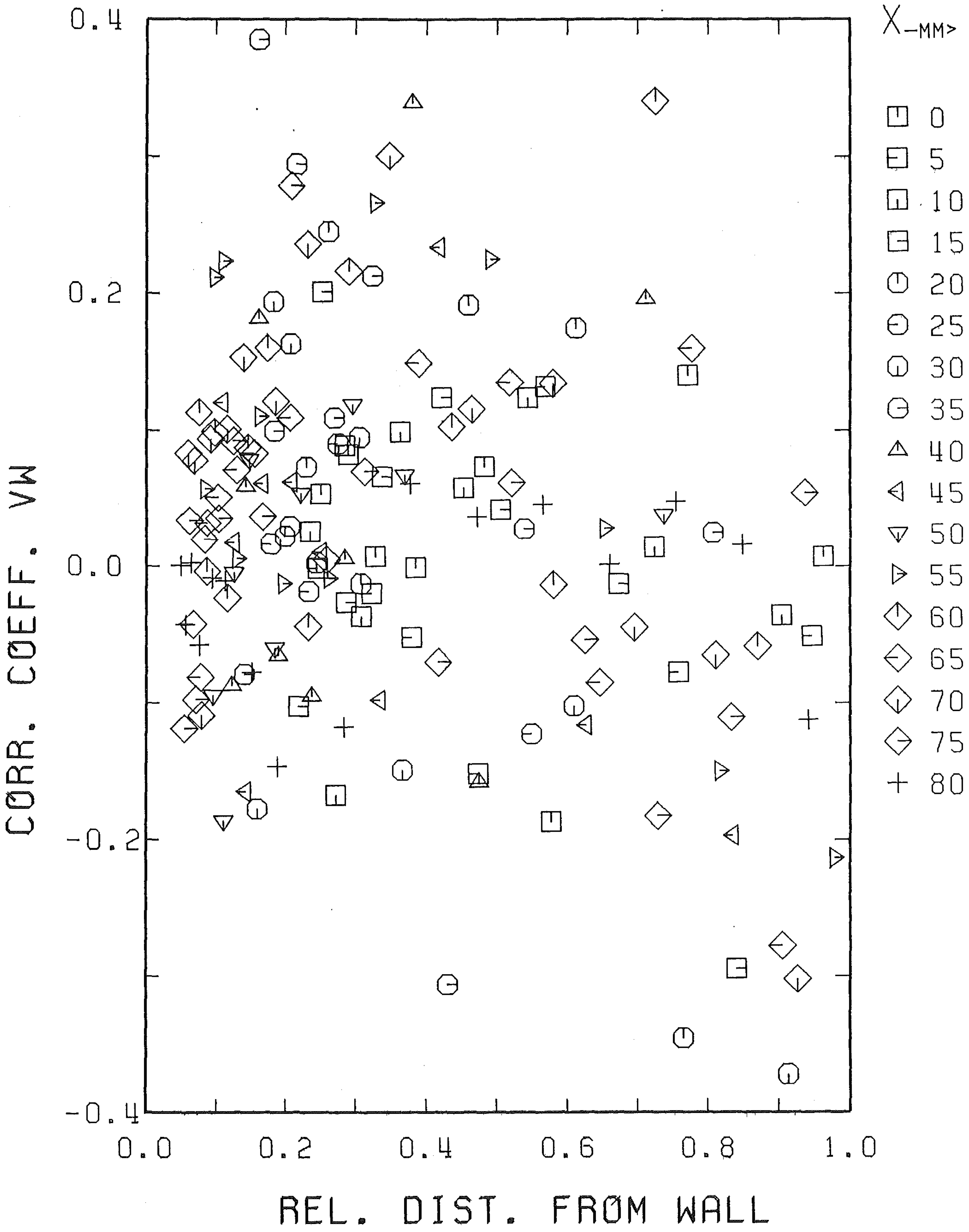


Fig. 35-2 Distribution of the correlation coefficient transverse to the wall in the x/y-part of quadrant 2

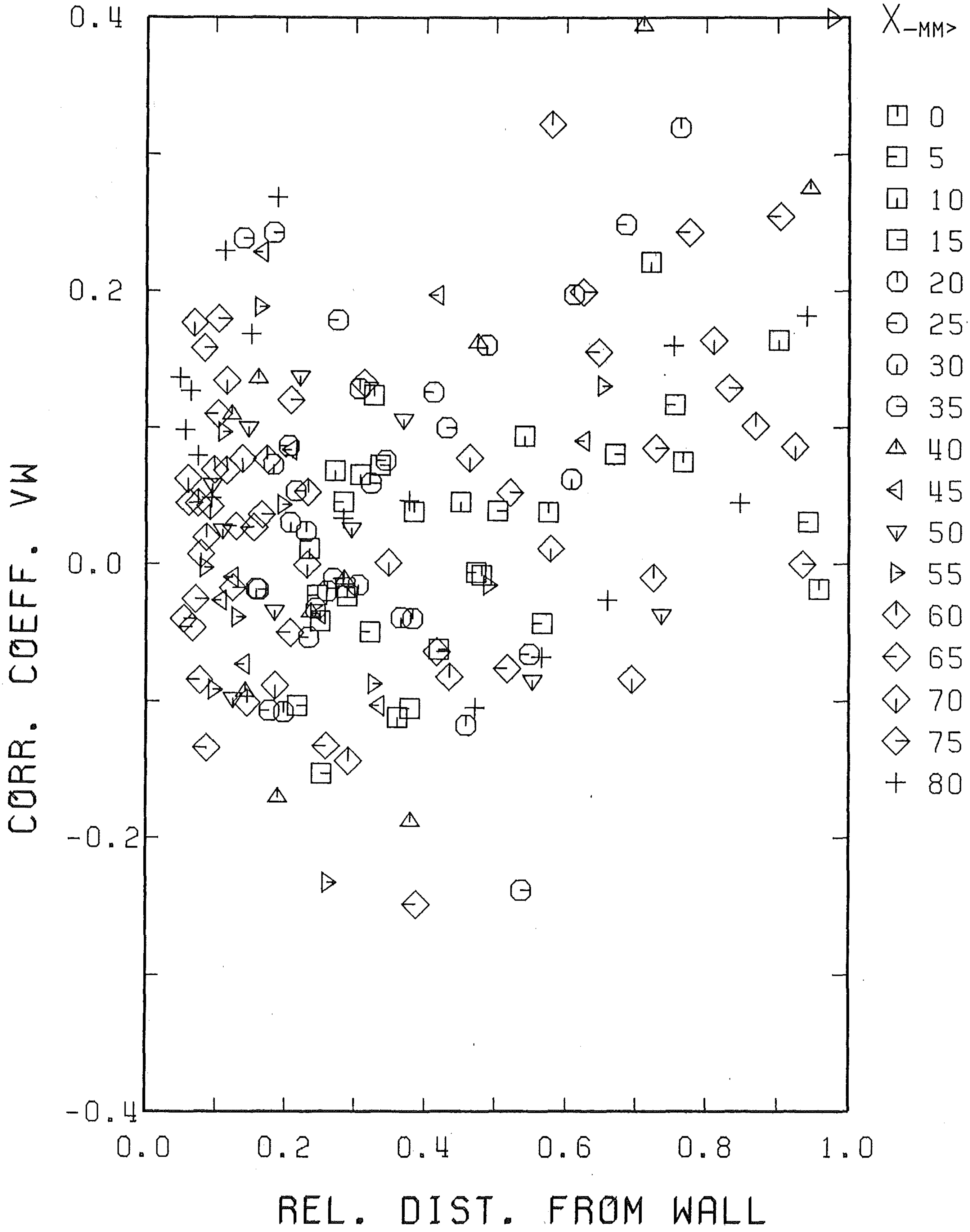


Fig. 35-3 Distribution of the correlation coefficient transverse to the wall in the x/y-part of quadrant 3

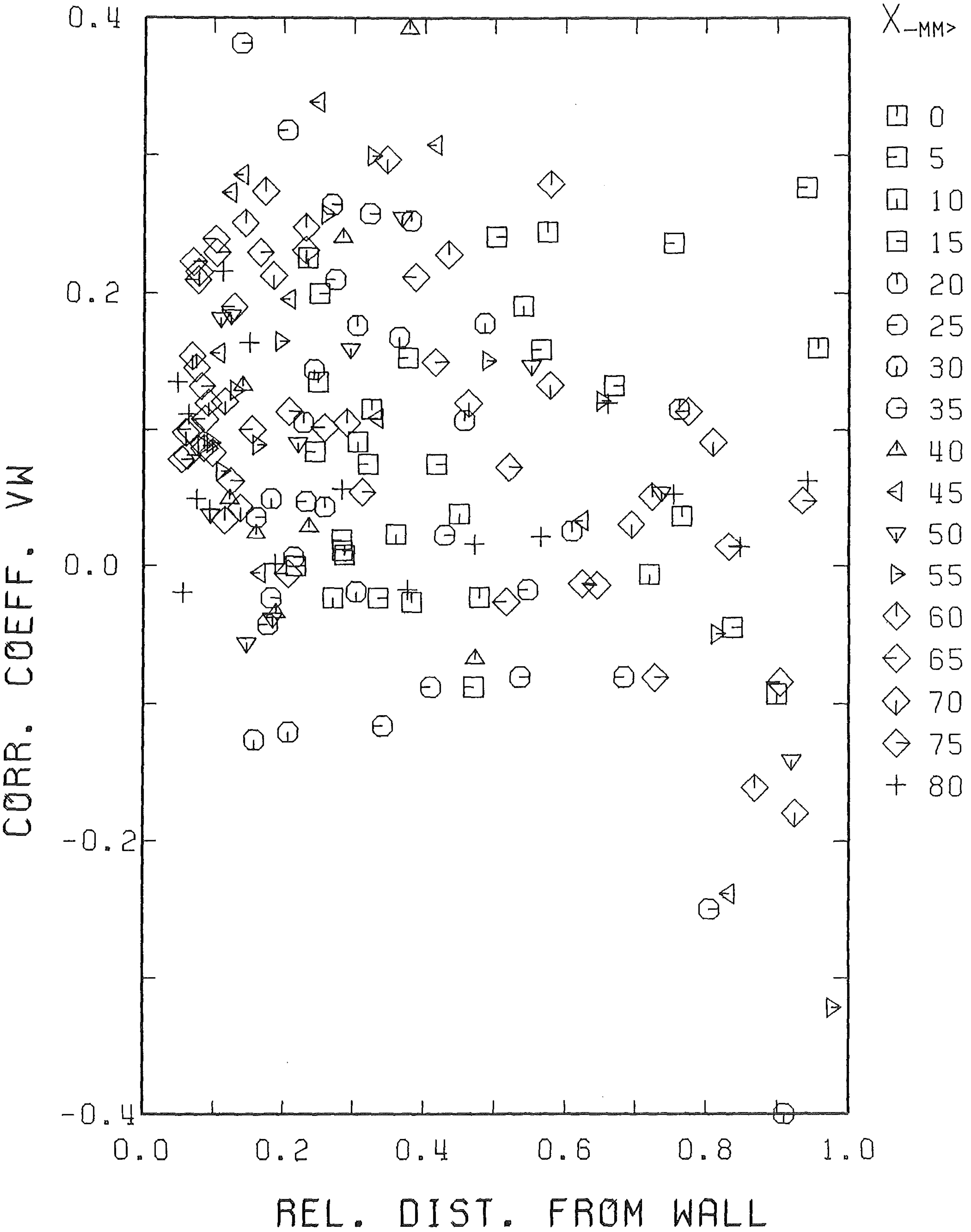


Fig. 35-4 Distribution of the correlation coefficient transverse to the wall in the x/y-part of quadrant 4

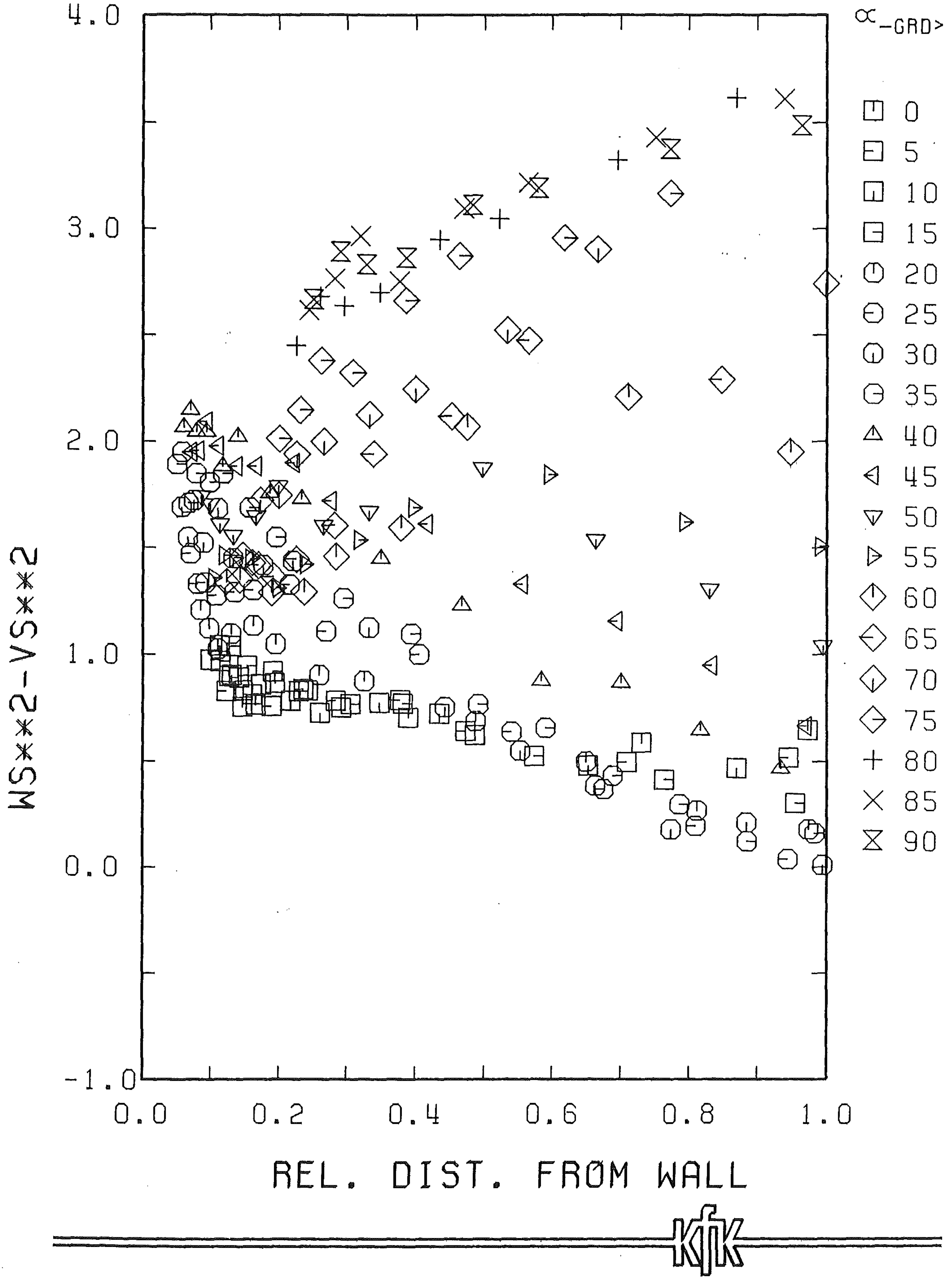


Fig.36-1 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the r/ϕ-part of quadrant 1

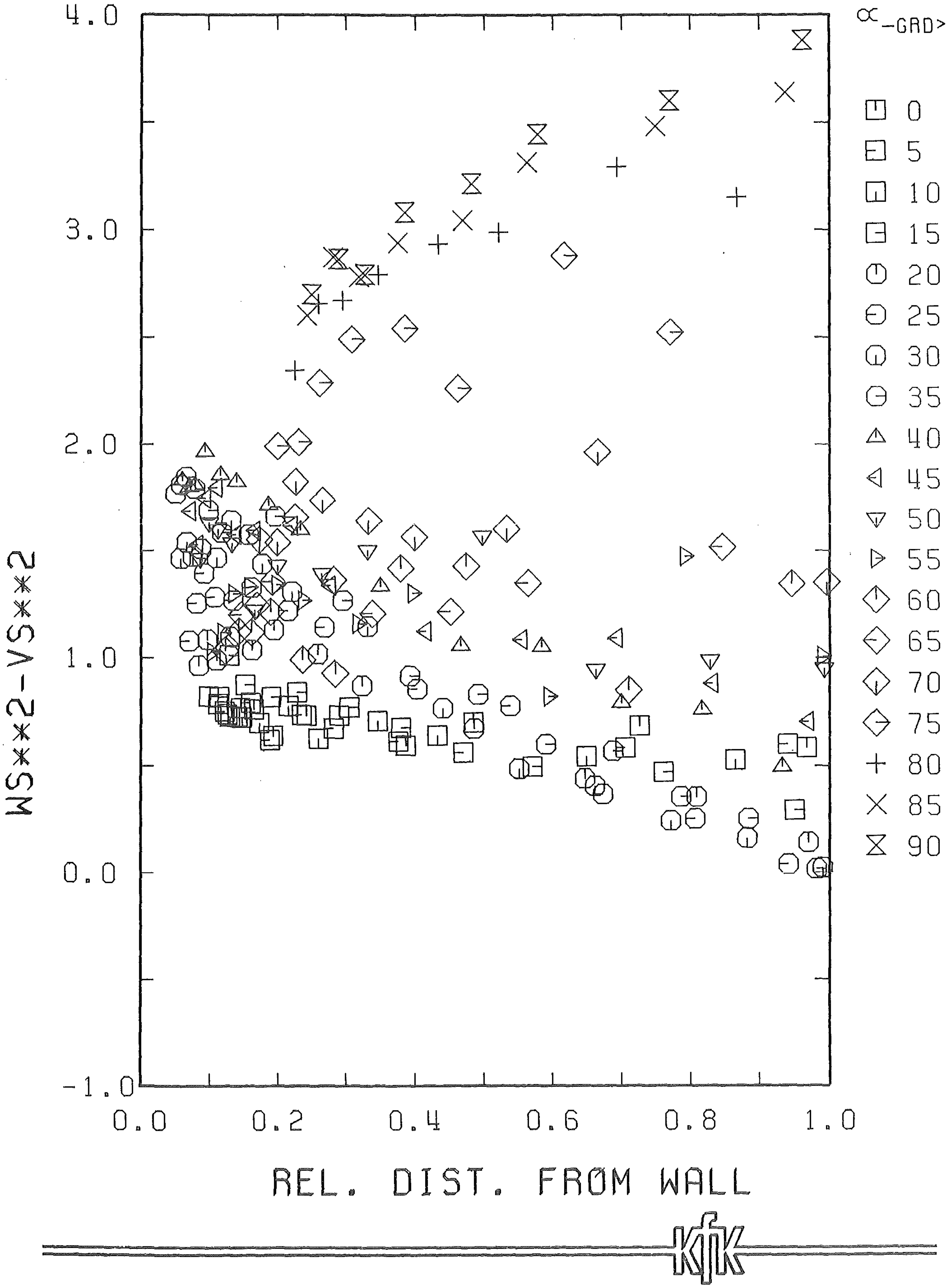


Fig.36-2 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the r/ϕ-part of quadrant 2

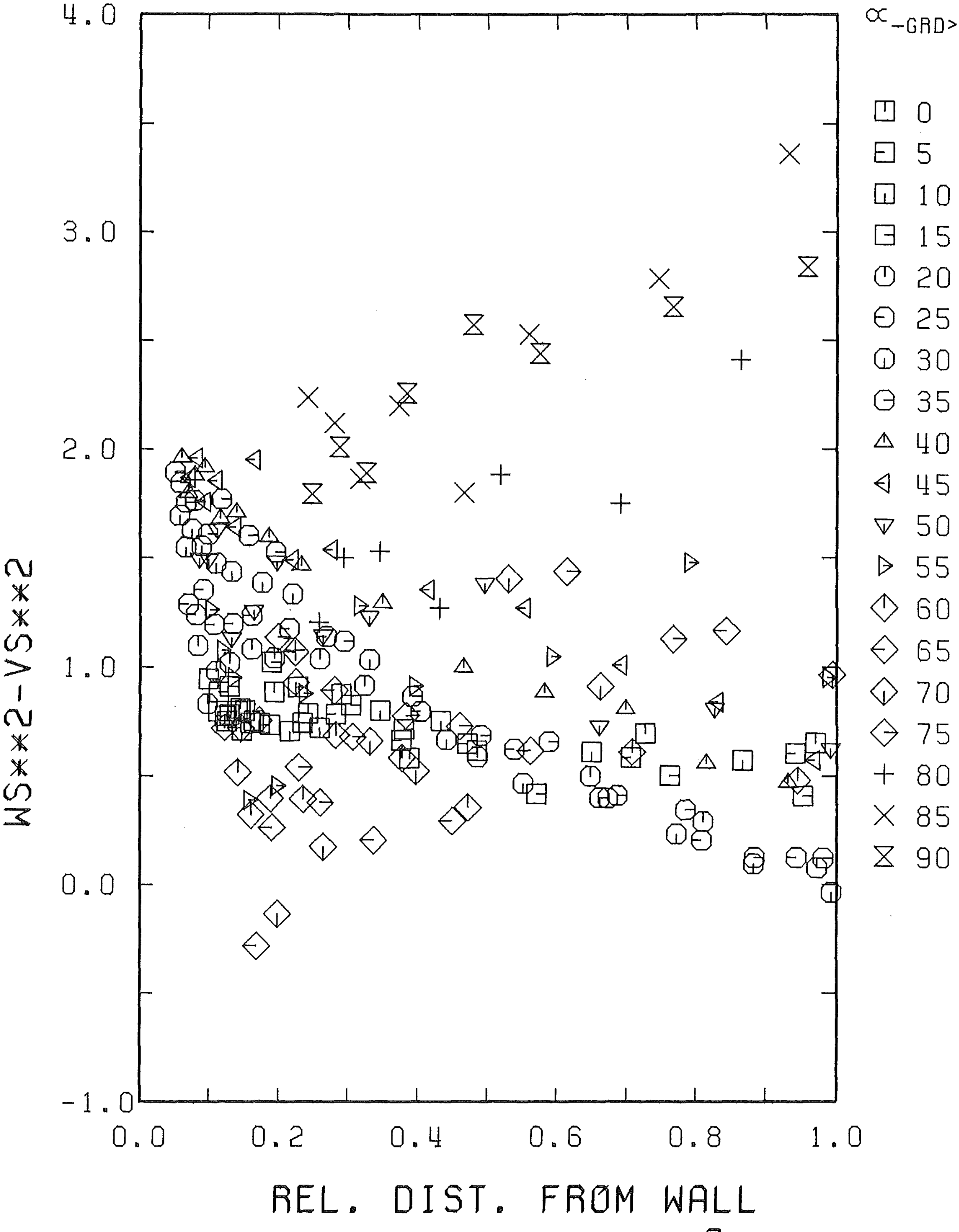


Fig.36-3 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the r/ϕ-part of quadrant 3

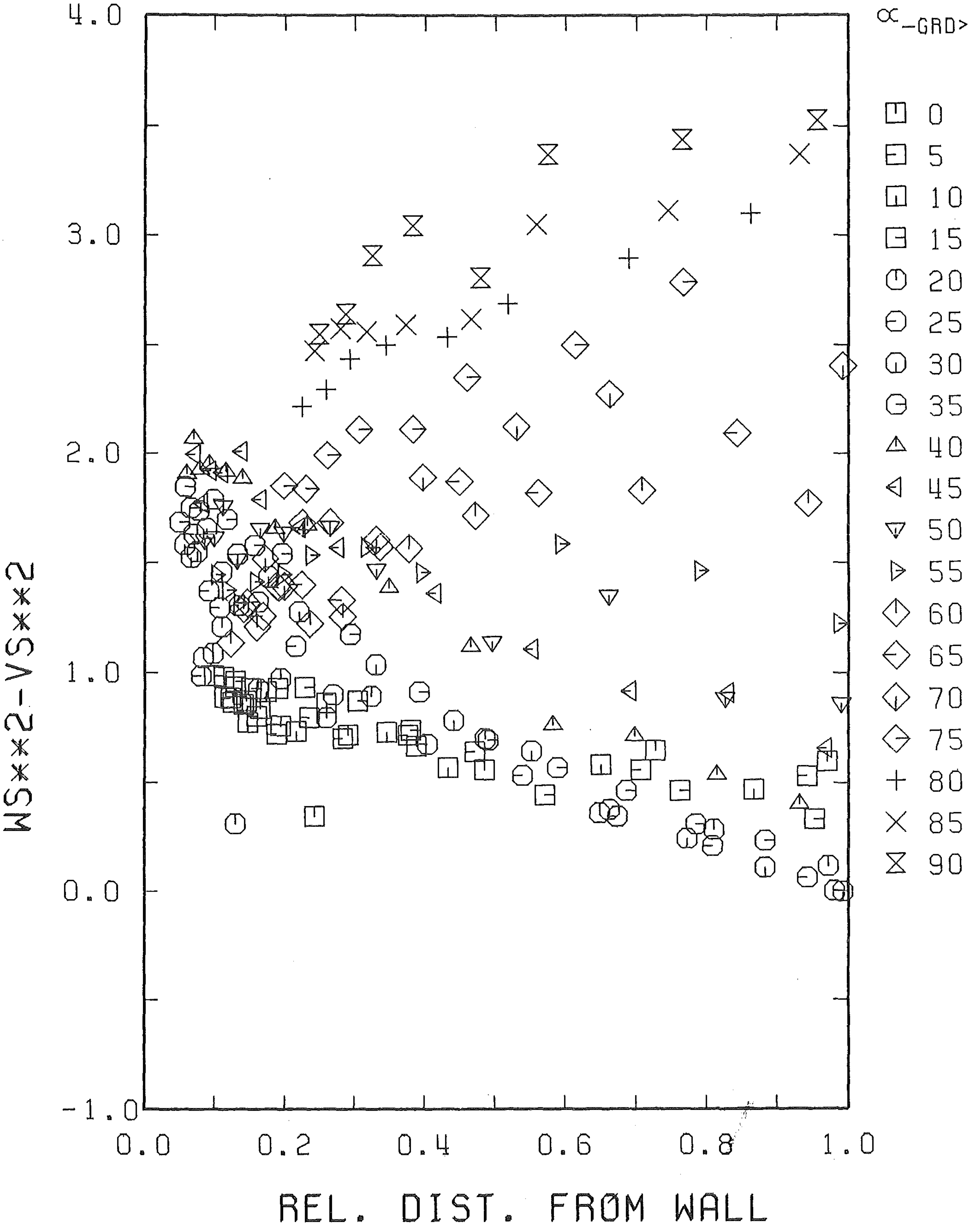


Fig.36-4 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the r/ϕ-part of quadrant 4

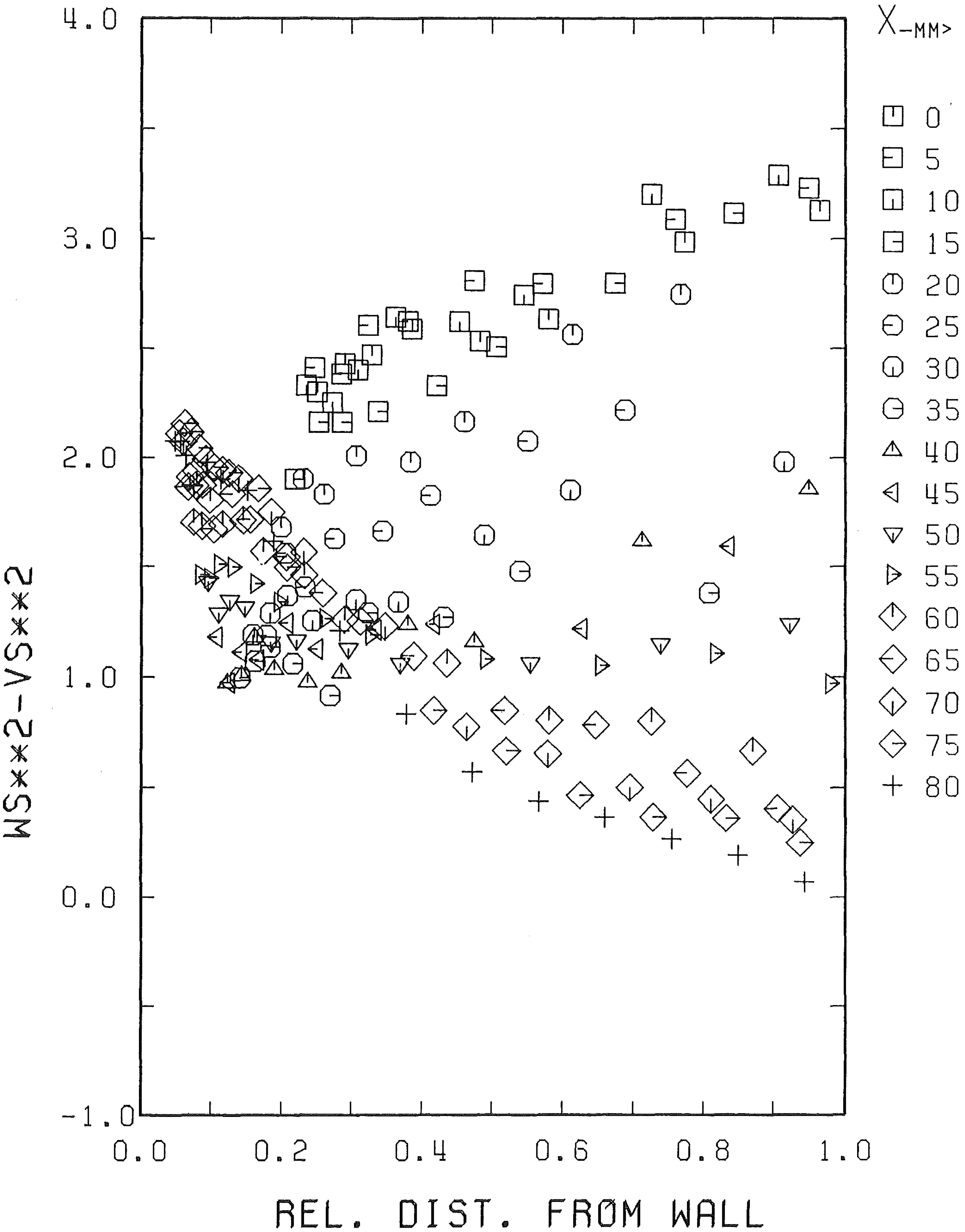
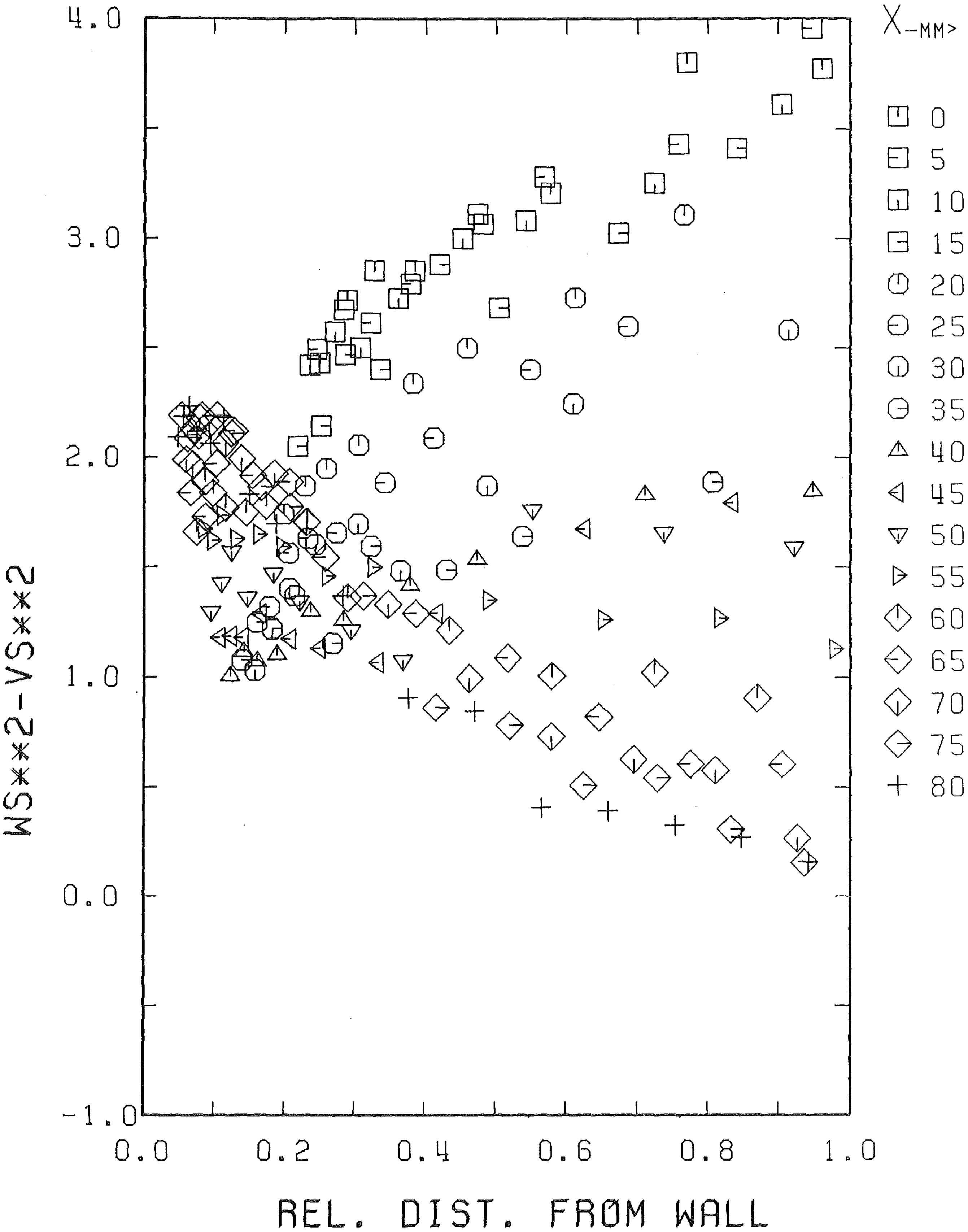


Fig.37-1 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the x/y-part of quadrant 1



KfK

Fig.37-2 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the x/y-part of quadrant 2

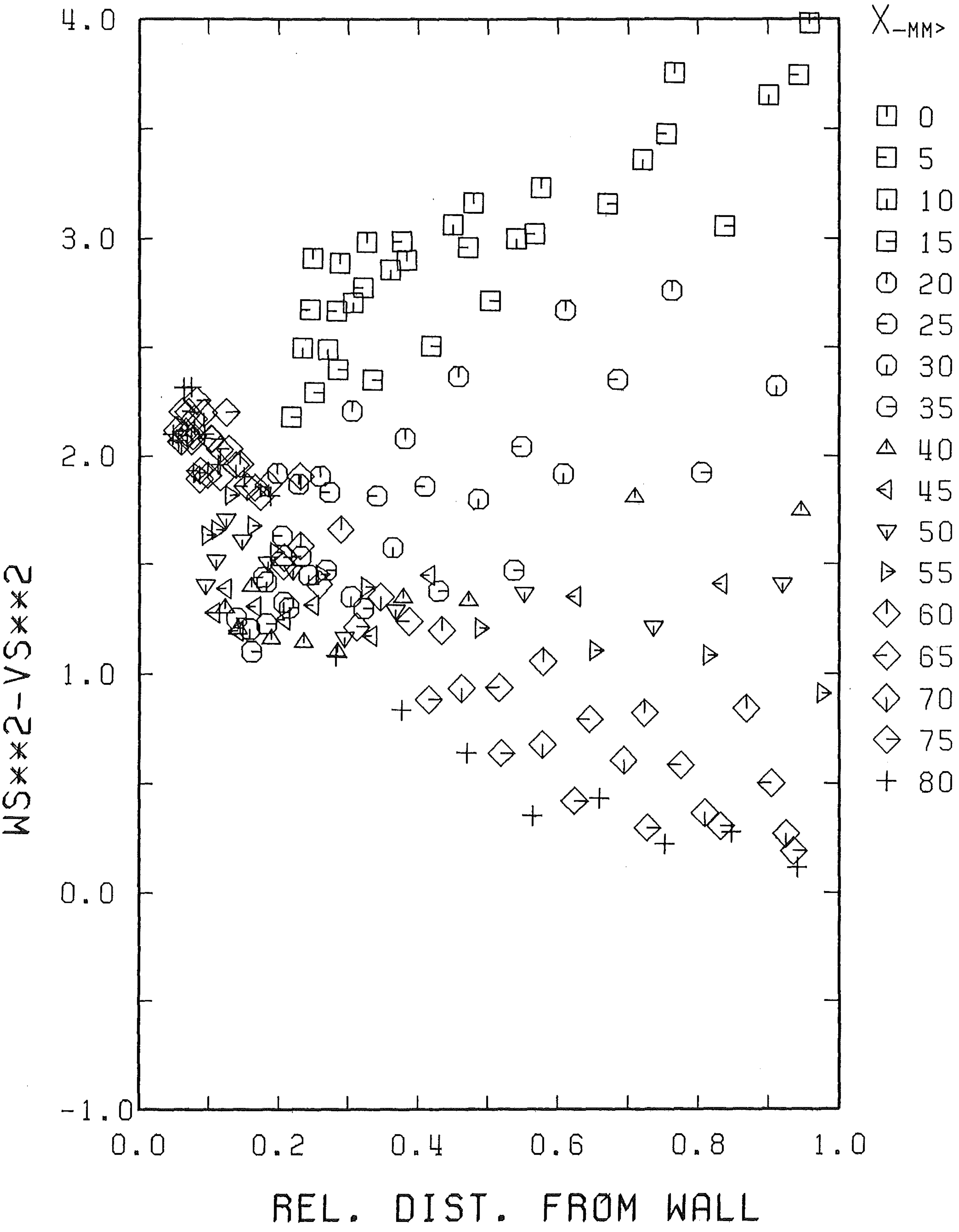


Fig.37-3 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the x/y-part of quadrant 3

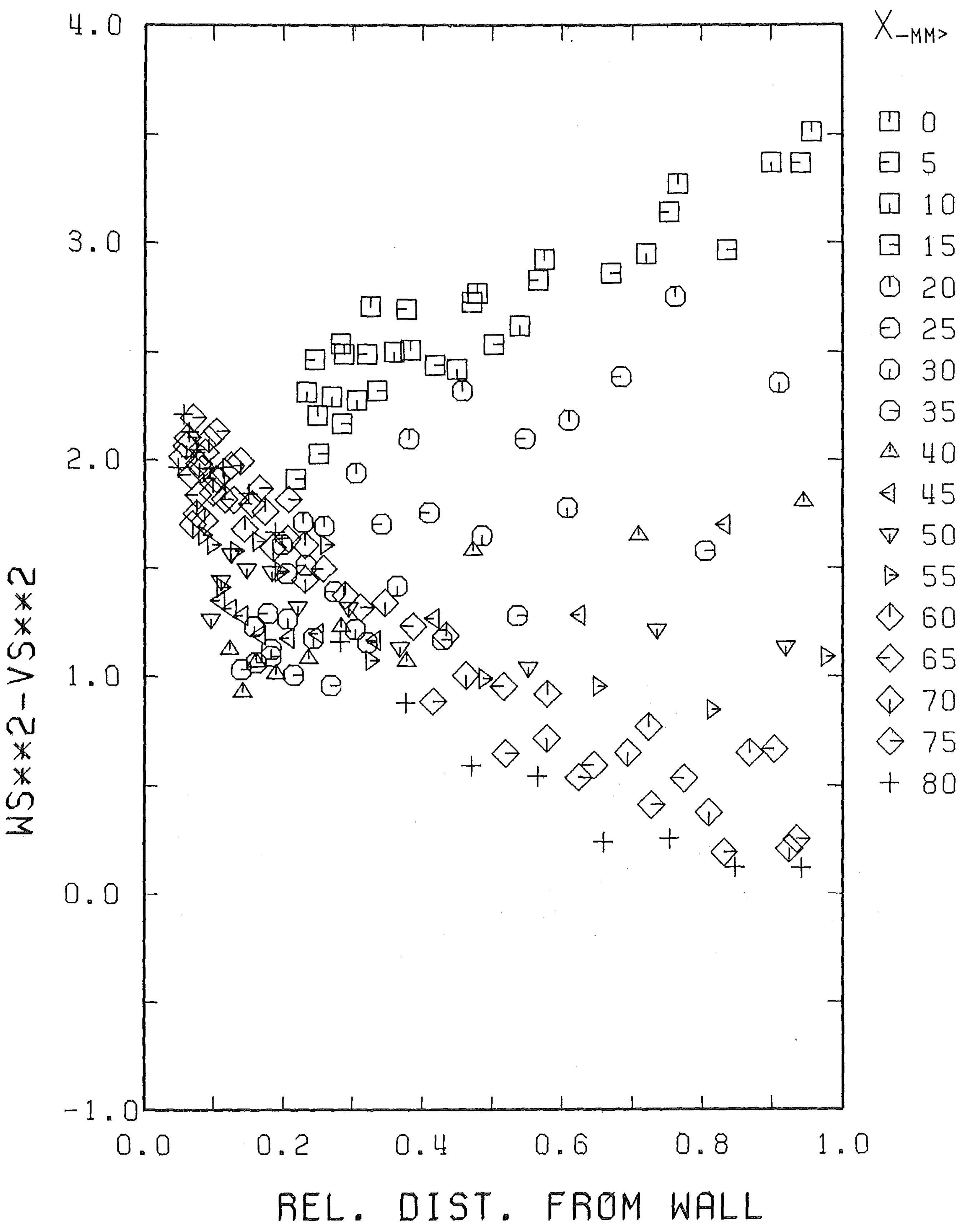


Fig.37-4 Distribution of the difference between the turbulence intensities parallel and perpendicular to the wall in the x/y-part of quadrant 4

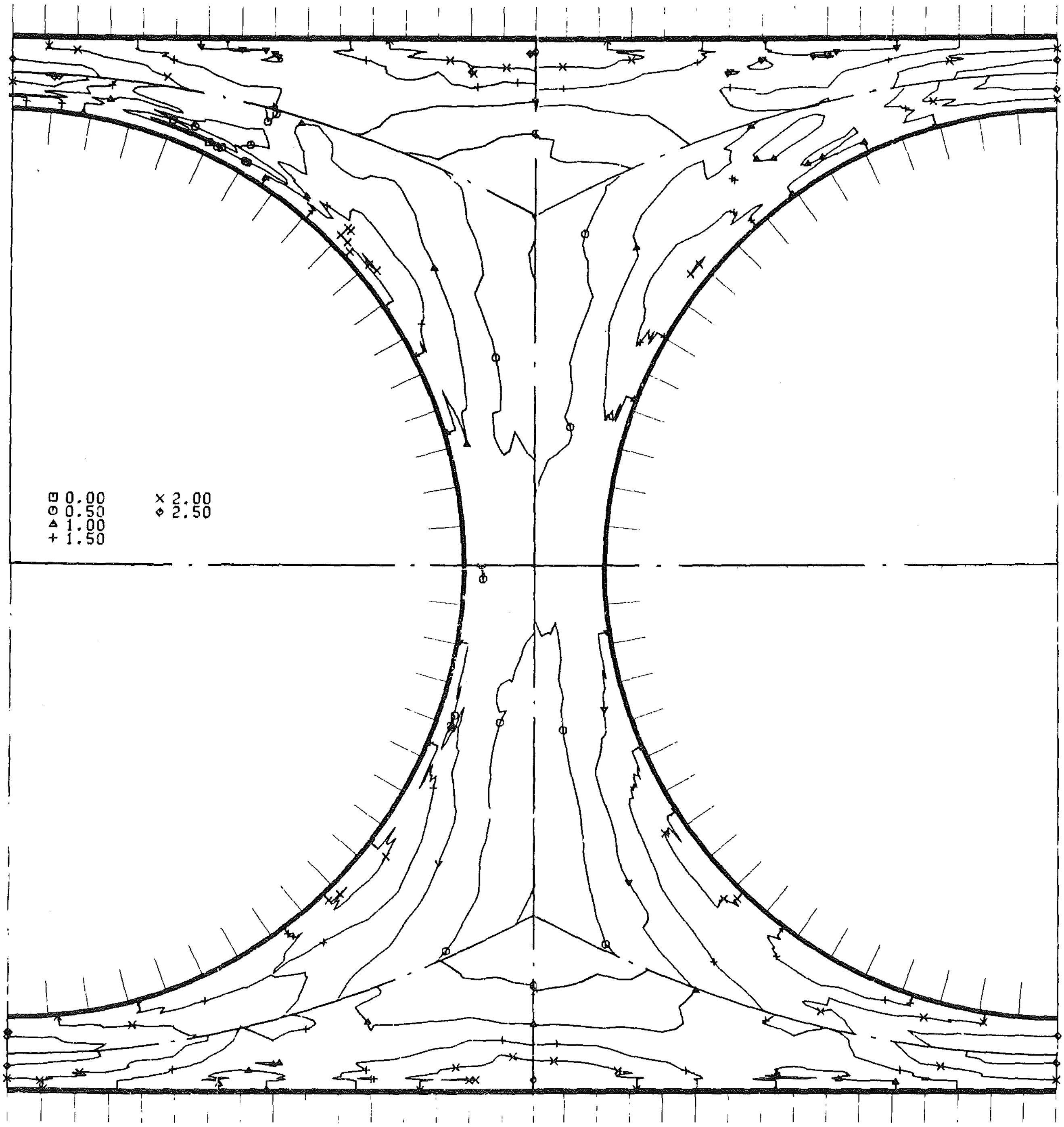
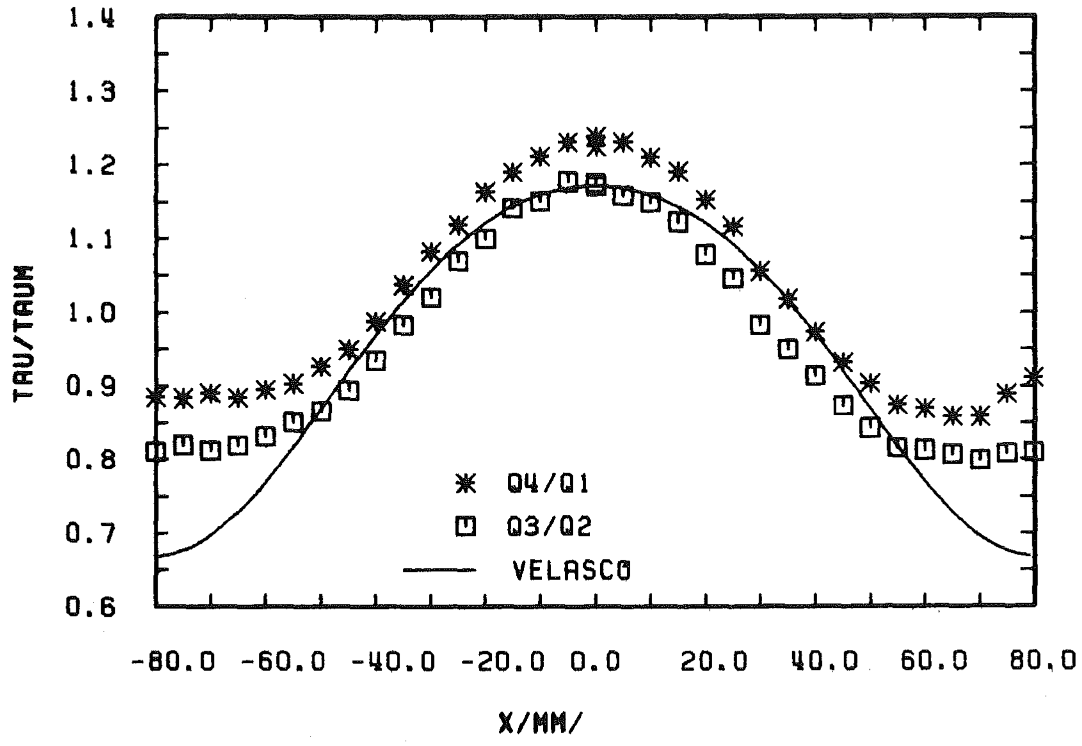


Fig. 38 Contours of the difference between the turbulence intensities parallel and perpedicularto the wall in the four quadrants



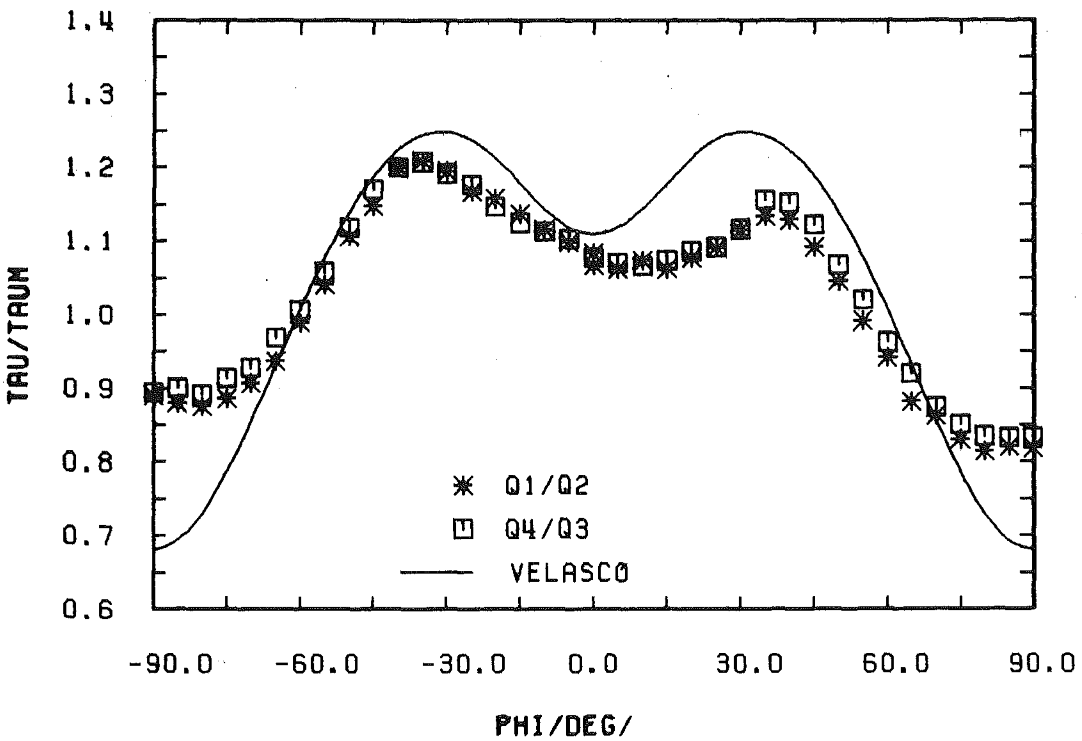


Fig. 39 Comparison between experimental wall shear stresses and prediction by VELASCO

Table 1: Geometry parameters of the four quadrants

	AH	AXS	ARW	F	P	D_h
	mm	mm	mm	mm^2	mm	mm
Q1	79.89	79.80	69.53	2578.28	189.02	54.6
Q2	79.92	79.86	69.53	2585.47	189.08	54.7
Q3	79.93	79.80	69.50	2584.75	188.97	54.7
Q4	79.95	79.80	69.50	2586.34	188.97	54.8

F:Flow area F=AH*AXS-0.25*3.1416*ARW^2

P:Wetted perimeter P=AXS+0.5*3.1416*ARW

D_h:Hydraulic diameter D_h=4*F/P

AH:Distance between the center of the rod and the channel wall

AXS:Distance between the center of the rod and the symmetry line between the rods

ARW:Radius of the rod

Table 2 : Average velocity in the quadrants and in the parts of the quadrants

Channel		Relative velocity U_{mit}	Velocity ms^{-1}	Discrepance %
Q1	R/Φ	0.7514	20.852	1.22
	X/Y	0.7267	20.167	0.96
Q1		0.7419	20.589	1.12
Q2	R/Φ	0.7313	20.295	1.49
	X/Y	0.7083	19.656	1.60
Q2		0.7225	20.050	1.53
Q3	R/Φ	0.7357	20.417	0.89
	X/Y	0.7145	19.828	0.73
Q3		0.7276	20.192	0.94
Q4	R/Φ	0.7510	20.841	1.16
	X/Y	0.7296	20.247	1.36
Q4		0.7428	20.614	1.24
$U_{av,mit}$		0.7338	20.364	------

U_{ref}=27.752 ms^{-1}

$U = U_{mit} * U_{ref}$

Discrepance=X/X_{av}

D_{max}=Maximal Discrepance in Symmetrical Parts

$D_{max,R/\Phi}$=1.49% (in Q2)

$D_{max,X/Y}$=1.60% (in Q2)

$D_{max,Q}$ =1.53% (in Q2)

Table 3: Maximum difference between the local velocities in the parts of the quadrants

Channel		** Relative Velocity U_{mit}	Discrepance %
Q1	R/Φ	0.452	0.60
	X/Y	0.448	0.84
Q2	R/Φ	0.457	0.60
	X/Y	0.439	3.83
Q3	R/Φ	0.430	5.40
	X/Y	0.453	0.28
Q4	R/Φ	0.479	5.39
	X/Y	0.467	3.38

** the relative velocity at four symmetrical points with maximum difference of velocity

WANDSCHUBSPANNUNGS-MESSERGEBNISSE

MITTLERE WANDSCHUBSPANNUNG TAUAV = 1.1473 PA

POSITION GRAD/MM	R/PHI VERS.-NR. 1	X/Y VERS.-NR. 2
0.0	1.0596	0.8895
5.0	1.0729	0.8679
10.0	1.0897	0.8384
15.0	1.1114	0.8392
20.0	1.1311	0.8488
25.0	1.1402	0.8537
30.0	1.1678	0.8818
35.0	1.1818	0.9105
40.0	1.1735	0.9506
45.0	1.1215	0.9947
50.0	1.0808	1.0317
55.0	1.0172	1.0911
60.0	0.9667	1.1266
65.0	0.9157	1.1639
70.0	0.8868	1.1828
75.0	0.8660	1.2026
80.0	0.8560	1.2102
85.0	0.8590	
90.0	0.8693	

Table 4: Wall Shear Stress in Quadrant 1

WANDSCHUBSPANNUNGS-MESSERGEBNISSE

MITTLERE WANDSCHUBSPANNUNG TAUAV = 1.0780 PA

POSITION GRAD/MM	R/PHI VERS.-NR. 5	X/Y VERS.-NR. 6
0.0	1.1100	0.8410
5.0	1.1044	0.8396
10.0	1.1162	0.8303
15.0	1.1045	0.8386
20.0	1.1208	0.8448
25.0	1.1342	0.8478
30.0	1.1601	0.8761
35.0	1.1793	0.9074
40.0	1.1740	0.9494
45.0	1.1355	0.9879
50.0	1.0864	1.0214
55.0	1.0317	1.0879
60.0	0.9794	1.1211
65.0	0.9172	1.1670
70.0	0.8978	1.1943
75.0	0.8638	1.2039
80.0	0.8472	1.2173
85.0	0.8541	
90.0	0.8517	

Table 5: Wall Shear Stress in Quadrant 2

WANDSCHUBSPANNUNGS-MESSERGEBNISSE

MITTLERE WANDSCHUBSPANNUNG TAUAV = 1.0972 PA

POSITION GRAD/MM	R/PHI VERS.-NR. 7	X/Y VERS.-NR. 8
0.0	1.1006	0.8278
5.0	1.0926	0.8366
10.0	1.0884	0.8291
15.0	1.0961	0.8359
20.0	1.1096	0.8491
25.0	1.1148	0.8690
30.0	1.1402	0.8837
35.0	1.1805	0.9137
40.0	1.1763	0.9548
45.0	1.1466	1.0036
50.0	1.0905	1.0420
55.0	1.0424	1.0924
60.0	0.9832	1.1230
65.0	0.9400	1.1655
70.0	0.8928	1.1753
75.0	0.8695	1.2026
80.0	0.8527	1.2002
85.0	0.8507	
90.0	0.8509	

Table 6: Wall Shear Stress in Quadrant 3

WANDSCHUBSPANNUNGS-MESSERGEBNISSE

MITTLERE WANDSCHUBSPANNUNG TAUAV = 1.1593 PA

POSITION GRAD/MM	R/PHI VERS.-NR. ~~4~~ 3	X/Y VERS.-NR. ~~1~~ 4
0.0	1.0417	0.8554
5.0	1.0660	0.8536
10.0	1.0757	0.8601
15.0	1.0879	0.8545
20.0	1.1088	0.8652
25.0	1.1372	0.8736
30.0	1.1520	0.8961
35.0	1.1672	0.9179
40.0	1.1603	0.9549
45.0	1.1310	1.0031
50.0	1.0811	1.0472
55.0	1.0224	1.0818
60.0	0.9728	1.1252
65.0	0.9363	1.1516
70.0	0.8970	1.1717
75.0	0.8833	1.1906
80.0	0.8616	1.1847
85.0	0.8710	
90.0	0.8646	

Table 7: Wall Shear Stress in Quadrant 4

Table 8: Measured Friction Factors

	Q1	Q2	Q3	Q4	Av
τ_{av}, Pa	1.147	1.078	1.097	1.159	1.120
U_m, m/s	20.59	20.05	20.19	20.61	20.36
$Re*10^4$	7.130	6.962	7.012	7.164	7.067
λ_τ	0.0185	0.0184	0.0184	0.0187	0.0185
$\lambda_{\Delta p}$	0.0194	0.0205	0.0203	0.0195	0.0199

Table 9 : Comparison between average velocities and wall shear stresses in all quadrants and the parts of the quadrants

Channel		U_{rel} m/s	$U^{1.8}_{rel}$	τ_{rel} Pa	D %
Q1	R/Φ	1.024	1.044	1.058	1.396
	X/Y	0.990	0.983	0.977	0.588
Q1		1.011	1.020	1.024	0.357
Q2	R/Φ	0.997	0.994	0.999	0.495
	X/Y	0.965	0.938	0.912	2.823
Q2		0.985	0.973	0.962	1.079
Q3	R/Φ	1.003	1.005	1.014	0.936
	X/Y	0.974	0.953	0.931	2.304
Q3		0.992	0.985	0.979	0.594
Q4	R/Φ	1.024	1.043	1.067	2.345
	X/Y	0.994	0.990	0.990	0.045
Q4		1.012	1.022	1.035	1.199

$U_{tot,av}$=20.363 m/s

$\tau_{tot,av}$=1.120 Pa

U_{rel}:Average velocity related to overall average

τ_{rel}:Average wall shear stress related to overall average

$D=(U^{1.8}_{rel}-\tau_{rel})/\tau_{rel}*100$ / % /