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THE RPR METHOD FOR THE DOORSTOPPER TECHNIQUE:

FOUR OR SIX STRESS COMPONENTS FROM ONE OR TWO BOREHOLES

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ABSTRACT

The importance of recording strain (or displacement) recovery during stress relief when conducting in situ stress measurements has been recognised by many authors as a means of assessing the quality of a measurement. This report shows an important new use for these strain recovery curves, as four components of the stress tensor can now be obtained from one modified doorstopper stress measurement using a parameter called the Recovered to Peak strain invariant Ratio (RPR). Modifications made to the standard doorstopper cell and to the standard field procedure are briefly described. These allow continuous recording of strain recovery while stress is being relieved, as well as the monitoring of temperature at the rock-cell interface. Then, a description of the finite element modelling allowing the production of curves relating the far field stress components in a plane parallel to the measurement plane to the stress component normal to this plane is given. Validation of the model is done by laboratory stress measurement simulations. Finally, comments on preliminary results of this method applied to the borehole deformation gauge stress measurement technique are shown.

SOMMAIRE

L'importance d'enregistrer en continu les déformations (ou les déplacements) récupérées suite au relâchement des contraintes lors des mesures de contraintes in situ, est reconue depuis longtemps comme un moyen d'assurer la qualité de ces mesures. Ce rapport présente une importante découverte associée à l'utilisation des courbes de déformations récupérées: la détermination d'un paramètre appellé RPR (de l'anglais Recovered to Peak strain invariant Ratio), qui permet l'obtention de quatre composantes du tenseur de contraintes à partir d'une seule mesure à l'aide du "doorstopper" modifié. Les modifications apportées à la cellule "doorstopper" ainsi qu'à la procedure de terrain conventionnelles sont brièvement décrites. Ces modifications permettent l'enregistrement en continu des déformations au fur et à mesure que les contraintes sont relâchées, de même que l'enregistrement de la température à l'interface roche-cellule et la lecture d'une résistance de précision.

Suit une description du modèle d'éléments finis adopté pour l'obtention des courbes qui relient les composantes du tenseur de contraintes in situ dans un plan parallèle au plan de mesure à la composante normale à ce plan. Des essais au laboratoire ont été réalisés pour valider ce modèle. Finalement, quelques commentaires sur des résultats préliminaires obtenus pour l'application de cette méthode à des cellules de type "Borehole Deformation Gauge" sont présentés.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX

LIST OF SYMBOLS

a, b, c, d	constants of a linear regression
α	function relating the peak strain invariants to σ_z
β, β'	angle between borehole and the X axis
E	Young modulus
$\bar{\epsilon}_{px}, \bar{\epsilon}_{py}$	strains at the borehole bottom
D_r, D_p	residual and peak strain invariants
$H_1, H_2, H_3,$	conventional borehole bottom stress concentration factors
H'_1, H'_2, H'_3	stress concentration factors corresponding to the drilled hole geometry giving peak invariant strains
ν	Poisson's ratio
l_i, m_i, n_i	director cosines in the xyz reference system
l'_i, m'_i, n'_i	director cosines in the x'y'z' reference system
RPR	recovered to peak strain invariant ratio
SR	stress ratio
$\bar{\sigma}_x, \bar{\sigma}_y, \bar{\tau}_{xy}$	stress components at the borehole end
$\sigma_x, \sigma_y, \sigma_z, \tau_{xy}$	far field stress components
x, y, z	borehole reference system
X, Y, Z	global reference system

1 - INTRODUCTION

In situ stress measuring techniques are numerous, each of them having their own advantages and disadvantages. Techniques based on the recovery principle (usually called overcoring techniques) are the most commonly used. In their standard configuration, they can be divided in two groups. The first group includes the triaxial cells, CSIR and CSIRO, that allow the calculation of the complete 3D stress tensor from a single borehole measurement, without prior knowledge of the principal stress orientation. The second group includes borehole deformation gauges and CSIR doorstopper cells, which require a minimum of three non parallel boreholes to calculate the 3D stress tensor, when the orientation of the principal components is not known *a priori*.

Contrary to what is generally believed and still reported in recent literature as in [1], the two last techniques, when used in a single borehole do not allow the estimation of three far field stress tensor components, since each measurement yields three independent equations containing four unknowns, these being the three components of the far field stress tensor in a plane perpendicular to the borehole axis, σ_x ,σ_y and τ_{xy} and the stress component parallel to this axis, σ_z. Figure 1 illustrates the reference system that is used in the paper. In order to determine the stress components in a plane perpendicular to the hole axis from a measurement in a single borehole, the far field stress component parallel to the hole axis must be known. Such is the case for hydraulic fracturing stress measurements, where the vertical stress is assumed to be a principal component equal to the overburden pressure. Under these circumstances, borehole deformation gauges and doorstopper cells also yield the complete 3D stress tensor from a single measurement, but it should be emphasized here that the vertical stress is not necessarily a principal component equal to the overburden pressure, which in the authors view, greatly limits the applicability of hydraulic fracturing stress measurements. A review of stress measurement techniques and means of establishing which method is best suited for measuring stresses in a given context is not the object of the

present paper, as such documents already exist [2]. The purpose of this paper is to present a method that allows four components of the 3D stress tensor to be obtained from a single measurement using the modified doorstopper cell. The modifications that have been made on the standard doorstopper cells and on the field measuring procedure in order to increase the potential of this technique and to provide a better stress measuring method to the users are also described. These modifications allow continuous controlled recording of strain recovery as well as monitoring of the rock-cell temperature while stress relief is in progress.

2 - ADVANTAGES AND DISADVANTAGES OF THE STANDARD DOORSTOPPER CELL STRESS MEASURING TECHNIQUE

In highly fractured rock masses or when the stress field induces core discing while drilling proceeds [3], only in situ stress measuring techniques requiring a short length of overcoring can be used. The standard doorstopper cell stress measuring technique [4] is the only currently used stress measuring method showing this advantage.

One must admit that the doorstopper cell stress measuring technique has, as well, the following advantages: (1) the deformability parameters required in the stress calculation model, whichever it is, can be obtained by loading the recovered core on which the doorstopper is glued in a biaxial Hoek type cell and by conducting subsequently, on the same core, a diametrical loading perpendicular to the direction of the major principal strain measured in the biaxial test; such a procedure reduces both the rock heterogeneity and the experimental errors effects to a minimum ([5], [3]); (2) a number of simple stress calculation models allowing to take into account anisotropy ([5], [6], [7], [8], [9]) combined with non linearity [3] are available.

Gray and Toews [10] have proposed to compare the strain invariants in the plane of measurement to establish greater confidence in stress measuring results. This is possible with the standard doorstopper cell measuring technique since the cell is essentially a four strain gauge rosette. However, Gill et al. [11] have shown that the invariants approach to detect outliers may be misleading; perfect match of the strain invariants can be obtained despite gauge debonding. Some stress measuring techniques allow strain or displacement recording while stress relief is in progress. The strain or the displacement recovery curves can then be used as a diagnose tool to evaluate the quality of the measurements by comparing them with theoretical strain recovery curves. This has been first suggested by Blackwood [12] and it still is the only

available means of doing so. The standard doorstopper cell stress measuring technique does not have this advantage.

In order to obtain recovery curves and to monitor rock-cell temperature variations while performing in situ stress measurements, the staff of the Rock Mechanics Laboratory of École Polytechnique de Montréal has devised [11] a series of simple and inexpensive modifications to standard doorstopper cells.

Concerning the disadvantages, the standard doorstopper technique requires that measurements be performed in three differently oriented boreholes in order to calculate the complete 3D stress tensor. The same holds for borehole deformation gauges but, the doorstopper will only require one hole diameter, which makes it less expensive in terms of drilling costs. As will be shown, the RPR method reduces the number of holes required from three to two, bringing the drilling costs and delays very close if not lower than what they are for CSIRO and CSIR triaxial cell stress measuring techniques.

3 - THE MODIFIED DOORSTOPPER TECHNIQUE

3.1 - The modified doorstopper cell

A RTD gauge (Resistance Temperature Detector) is cemented in an appropriate cut machined on the flat face of the doorstopper cell, just beside the strain gauge rosette (Figure 2). A hole is drilled from that cut towards the doorstopper cell terminal case to allow a way for the RTD gauge connecting wires. This hole is subsequently plugged with silicone paste. A 120 ohm precision resistor is also included in the modified cell. This resistor allows to detect any instrument related problems as it should give constant readings.

Each of the conductors of a waterproof multiwire shielded electrical cable of the appropriate length is welded directly to the doorstopper terminals and to the connecting wires of the RTD gauge. The connections are waterproofed by epoxy casting in a cylinder. The latter is cemented to the protective plastic shell of the doorstopper cell and is long enough to cover the stripped part of the cable, giving additional mechanical resistance to the connections (Figure 2).

A small longitudinal groove is made on the protective plastic shell of the doorstopper cell to correctly orient the latter on the installation tool (Figure 2).

3.2 - The modified field procedure

The borehole flat ends are polished and cleaned as with the standard doorstopper cell field procedure. The installing tool of the modified cell consists in a set of hollow rods at the end of which is attached a hollow aluminium cylinder having the same diameter as the borehole. The modified doorstopper cell, on which a layer of adhesive has been spread, sits in the aluminium cylinder hole while it is kept properly aligned

by slightly tightening a set screw in the groove. The electrical cable runs through the rods of the installing tool as they are inserted into the borehole. In unstable rock formations, the installation can be made inside the drill rods.

Once the doorstopper cell is in the proper position at the flat end of the borehole, a slight pressure is maintained on the installation rig for the curing time of the adhesive to insure an adequate bonding of the cell on the rock surface. The installation tool is then removed, leaving in place only the doorstopper cell attached to the electrical cable. The drill water swivel must allow the cable through. A slight tension is applied to the cable as the rods are inserted into the borehole in order to prevent it from being squeezed or cut. Proper connections of the cable conductors to the data acquisition system are made. The drill penetration measuring sensor is also connected to the latter.

Once it is decided to proceed with the measurement, the stress relief begins and continuous readings of the strain gauges, of the high precision resistance, of the temperature detector and of the drill penetration sensor are taken until required.

As of writing these lines, a miniature down the hole intelligent data acquisition system which plugs directly on a standard doorstopper cell, is being developed and tested by École Polytechnique and Hydro-Québec. This system simplifies the recording of the strain recovery curves in deep holes, since long lead wires are not present, increasing strain gauge stability. Moreover, battery operation facilitates installation, as no wires run through the drill rods.

3.3 - Monitoring of the temperature

With the standard doorstopper cell stress measuring technique, it is assumed that the rock-cell temperature is the same when the initial and the final strain readings are taken. To achieve such conditions when the temperature of the drilling water is different from that of the rock mass (which is generally the case), one

must take the initial strain readings before feeding the drilling water and wait, after completion of the overcoring, in order to attain initial temperature conditions before taking final strain readings. This holds true even if there is a dummy gauge, since the latter will deform differently under given temperature conditions, particularly for the initial readings where the boundary conditions are not the same for the material on which the dummy gauge is bonded, compared to the flat end of a borehole. At most, thermal effects on the electrical system (variations in resistivity) which can be quite important in some cases, will be properly compensated [13].

With the modified doorstopper cell stress measuring technique, the monitoring of the rock-cell temperature as the stress is being released can be used in a number of ways which have been presented in earlier papers by [14].

3.4 - Previous work related to continuous recording of strain recovery

White et al. [15] have described the use of "flat and hemispherical ended plexiglass 'doorstoppers' devices" which allow strain readings while stress relief is in progress. No description of the cell neither of the field procedure are given and no strain relief curves are presented. These cells do not allow temperature monitoring.

Jenkins and McKibbin [16] briefly describe a series of modifications made to the standard doorstopper cell by the US Bureau of Mines to allow continuous strain and temperature monitoring during overcoring, a thermistor being used as a temperature sensor. No strain relief curves are presented.

Thompson et al. [17] have modified the standard triaxial CSIR cell [11], in order to make strain observations during overcoring; to monitor the temperature as drilling proceeds, they have replaced the dummy strain gauge by a thermistor which monitors the air temperature inside the pilot hole. Gill et al. [11] also made modifications to the standard CSIR triaxial cell in order to record strain recovery curves.

The authors are aware of the fact that with the doorstopper technique, measurements must be performed in three differently oriented boreholes. This is the major inconvenience of the method; however, in many of the situations they have experienced, the modified doorstopper cell stress measuring technique was the only one that could be used. Moreover, use of the RPR method reduces the number of boreholes required to calculate a 3D stress tensor from three to two.

4 - DETERMINING THE FOURTH STRESS COMPONENT

4.1 - Empirical relationships

It seems difficult to believe that four stress components can be obtained by measuring strains in a plane, as only 3 independent equations can be derived from the measured strains. The following equations relate the far field stress components to the stresses measured at the borehole bottom:

$$\overline{\sigma}_x = H_1\sigma_x + H_2\sigma_y + H_3\sigma_z \tag{1}$$

$$\overline{\sigma}_y = H_1\sigma_y + H_2\sigma_x + H_3\sigma_z \tag{2}$$

$$\overline{\tau}_{xy} = (H_1 - H_2)\,\tau_{xy} \tag{3}$$

where $\overline{\sigma}_x$, $\overline{\sigma}_y$, $\overline{\tau}_{xy}$ are the stress components at the borehole end and σ_x, σ_y, σ_z and τ_{xy} are the far field stress components. H_1, H_2, H_3, are the stress concentration factors which are a function of the Poisson's ratio and which can be obtained from the following empirical relationships [7]:

$$H_1 = 1.32 + .08\nu\,(1 + \nu) \tag{4}$$

$$H_2 = -0.12 + 0.18\nu\,(1 + 2.55\nu) \tag{5}$$

$$H_3 = -1.09\,(0.33 + \nu) \tag{6}$$

If σ_z could be obtained, it would then be possible to calculate the stress components σ_x and σ_y in equations 1 to 3 (which, again, is not possible with the conventional technique). The information necessary to determine σ_z, comes from the strain recovery curve and consists in finding the relationship that exists between the Recovered to Peak Ratio, RPR, and the Stress Ratio, SR. RPR(ν) is given by,

$$RPR = \frac{D_r}{D_p} \tag{7}$$

where D_r is the mean recovered strain invariant in the measurement plane and D_p is the mean peak strain invariant obtained during the stress relief drilling as shown in Figure 3.

As for a given stress state, the stress concentration factors are known to be a function of the Poisson's ratio only, it is obvious that RPR will also be a function of Poisson's ratio. The stress ratio SR is given by,

$$SR = 2\frac{\sigma_z}{\sigma_x + \sigma_y} \tag{8}$$

where σ_z is the far field stress component parallel to the hole axis and the sum $\sigma_x + \sigma_y$ is the far field stress invariant in the measurement plane.

The relationship between SR and RPR gives the fourth equation required to completely determine the four unknowns in equations 1 to 3, without requiring extra strain gauges, boreholes or complicated modelling. It only requires using information already available on the strain recovery curve.

4.2 - Obtaining the SR-RPR relationships

Calculating strain recovery curves for doorstopper stress measurements using an analytical solution is extremely difficult and such attempts have given very approximate solutions for particular load cases [19] that cannot be used in the present analysis. As powerful finite element codes are available on micro computers, it was found more practical to simulate stress measurements using numerical models and to validate the results by using physical models in the laboratory.

The COSMOS/M finite element code from Structural Engineering was used to obtain the strain recovery curves for different load cases and Poisson's ratios. In order to investigate the influence of the σ_x/σ_y ratio on the parameter RPR, 3D finite element analyses were performed by varying the σ_x/σ_y ratio from 1 to 2, keeping $\sigma_x + \sigma_y$ constant for a given σ_z. Figure 4 illustrates a detail of the 3D mesh that was used for the analyses. The RPR was found to depend only on the Poisson's ratio, and on the SR value. In fact, this can be demonstrated by expressing RPR by including stress-strain relationships in equations 1, 2 and 7. Having H_1, H_2 and H_3 as conventional borehole bottom stress concentration factors and H'_1, H'_2 and H'_3 as stress concentration factors corresponding to the drilled hole geometry giving peak invariant strains, one can express RPR as follows using equations 1 and 2 and stress-strain relationships,

$$RPR = \frac{H_1 + H_2 + SRH_3}{H'_1 + H'_2 + SRH'_3} \tag{9}$$

In this equation, the only stress dependent parameter is SR and it is independent of the ratio σ_x/σ_y. Concerning the influence of the far field shear stress components τ_{xz} and τ_{yz}, Gray and Toews [10] had demonstrated that he stresses at the centre of the borehole bottom were independent of τ_{xz} and τ_{yz} because of the symmetry of the borehole bottom. The same demonstration applies to the drilled hole bottom

geometry at the moment the peak strains are measured, so the analyses can be done by neglecting the influence of these shear stress components.

For these reasons an axisymmetric model was considered to be suited for the analyses and the mesh used is shown in Figure 5. The strain recovery curves in Figure 6 where obtained for different Poisson's ratios using the axisymmetric model, and show the influence of ν when the SR is kept constant at a value of 1. Figure 7 shows strain recovery curves for a Poisson's ratio of 0.1 for different SR values. Combining various SR and ν values allows to plot the graph in Figures 8 and 9, which can be used for calculation purposes. Figure 8 covers the SR range from 2 to 8 while Figure 9 gives the SR values between 0 and 2, these being the most commonly used. SR values for Poisson's ratios other than the ones plotted can be obtained by interpolation. The curves in Figure 8 and 9 were obtained by a least squares fit on the results of the finite element analyses using the following equation:

$$SR = a + b[\cot(d * (1 + RPR))] + c[\cot(d * (1 + RPR))]^2 \tag{10}$$

where a, b, c and d are the regression factors obtained by least squares. Due to the shape of the SR-RPR relationship, a trigonometric function of the type $y = \cot(x)$ was found to be the most suited for the regression analyses.

4.3 - Calculating the four stress components

From equations 1, 2, 3 and 8, the following system of simultaneous linear equations can be solved for σ_x, σ_y, τ_{xy} and σ_z.

$$\sigma_y = \frac{H_1\bar{\sigma}_y - H_2\bar{\sigma}_x - H_3(H_1 - H_2)\sigma_z}{H_1^2 - H_2^2} \tag{11}$$

$$\sigma_x = \frac{H_1\bar{\sigma}_x - H_2\bar{\sigma}_y - H_3(H_1 - H_2)\sigma_z}{H_1^2 - H_2^2} \tag{12}$$

$$\tau_{xy} = \frac{\bar{\tau}_{xy}}{H_1 - H_2} \tag{13}$$

$$\sigma_z = SR \left[\frac{\sigma_x + \sigma_y}{2} \right] \tag{8}$$

With this system of equations, one problem can occur in the case where $\bar{\sigma}_x = \bar{\sigma}_y = 0$ as equations 11 and 12 are not independent. This may happen, for example, in a vertical drill hole in undisturbed sedimentary rocks with a Poisson's ratio of about 0.35, where the in situ stresses are only caused by gravity loading. In such a situation, the horizontal stress components are equal and their effect, combined with the vertical stress component, induce a null stress state at the borehole bottom. In such a situation, $\bar{\sigma}_x = \bar{\sigma}_y = 0$, RPR = 0 and σ_z can be obtained from the following equation:

$$\sigma_z = \alpha \times (\bar{\epsilon}_{px} + \bar{\epsilon}_{py}) \times E \tag{14}$$

where α is a function of the Poisson's ratio as given in Table I. These values were obtained by finite element analyses. $\bar{\epsilon}_{px}$ and $\bar{\epsilon}_{py}$ are the strains measured in micro strains at the peak and the Young's modulus is expressed in MPa. The resulting stress is expressed in Pa.

TABLE I

ν	0.0	0.1	0.2	0.3	0.4	0.49
α	3.0058	3.0957	3.2439	3.4521	3.7174	3.8708

As an example, if $\overline{\epsilon}_{px} + \overline{\epsilon}_{py} = 350\mu$ strains, and the rock has a Poisson's ratio of 0.35 and a Young's modulus of 7 GPa, $\sigma_z = 3.5848 * 350 * 7000 = 8.78$ Mpa. Once σ_z is known, σ_x and σ_y can easily be estimated from the SR ratio. For the example given, RPR = 0 gives an SR of 1.88, so $\sigma_x = \sigma_y = 4.67$ MPa. This corresponds to the particular case mentioned previously in a gravitational stress field. Having a vertical stress of 8.78 MPa gives a horizontal stress of $\nu/(1-\nu) * 8.78 = 4.72$ Mpa. The difference of 0.05 MPa is related to the fact that the Poisson's ratio corresponding to null stresses at the hole bottom in a gravitational stress field is not exactly 0.35, and also to the fact that the linear interpolation between Poisson's ratios of 0.30 and 0.40 is not very accurate as the relationship between α and ν is not linear.

4.4 - Calulating the 3D stress tensor

Having four independent equations per hole, it is now possible to calculate the 3D stress tensor without prior knowledge of the principal stress orientation, with only two holes instead of the three holes required until now. If one principal stress orientation (not intensity) is known, the complete 3D stress tensor can be obtained with a single measurement. Hydraulic fracturing not only requires the knowledge of a principal stress orientation, but its intensity also has to be guessed if not otherwise measured. Having to drill a maximum of two holes instead of three represents time and money savings of 33% on a doorstopper stress measurement campaign. It also allows to concentrate the measurements in a smaller

volume of rock, which is important if the stress field is not homogeneous. The demonstration that 6 of the 8 equations obtained from two measurements in two non parallel or non orthogonal boreholes are independent, is given in appendix A.

5 - EXPERIMENTAL VALIDATION OF THE RPR METHOD

In order to validate the proposed methodology, stress measurement simulations were performed in the laboratory on different types of materials. These laboratory simulations allow to control the applied stress intensities and orientations, but also allow the introduction of experimental factors that can affect the quality of the measurement.

5.1 - Validation on concrete and rock specimens

As continuous monitoring of doorstopper strain recovery curves has been going on for more than 15 years at École Polytechnique, laboratory data was available and could be used to validate the methodology. Fortin [20] performed doorstopper stress measurement simulations in the laboratory on one concrete and two limestone blocks with a SR ratio of 0, as no stresses were applied in the direction of drilling. Tests on concrete and on limestone 1 were performed with a σ_x/σ_y ratio of 1 and for the test on limestone 2, this ratio was of 2. The invariant strain recovery curves are shown in Figure 10. The data relative to these three tests is given in Table II. The results obtained from the RPR curves are in very good agreement with the experimental results. It should be noted that the limestone showed an anisotropic behaviour, which does not seem to affect the validity of the methodology.

Corthésy and Gill [9] also performed stress measurement simulations on synthetic and natural rocksalt, and the strain recovery curves, one of which is presented in Figure 11 gives the RPR value corresponding to the correct SR as shown in Table II. An interesting element related to this test is that the strain recovery curve had to be corrected for temperature effects following a methodology discussed in Corthésy and Gill [9]. It should also be noted that the rocksalt tested showed a pronounced non linear elastic behaviour upon loading, and the correct SR value is still obtained. Evaluation of the influence of

anisotropy and non linearity, a behaviour shown by all rocks with different intensity [3] is currently being investigated in relation with the RPR method.

TABLE II

Test material	σ_x/σ_y ratio	Poisson's ratio	RPR	Applied SR	Calculated SR
concrete	1	.18	.8536	0.0	-0.035
limestone 1	1	.29	.8492	0.0	0.004
limestone 2	2	.33	.8498	0.0	-0.005
rocksalt	1	.34	.8428	0.0	0.080

5.2 - Validation on an epoxy cylinder with applied axial stress

The previous validations all being done with an SR = 0, an experimental setup allowing to vary SR from 0 to 5 was used to further validate the RPR method. Also, since the numerical simulations were performed by supposing a linear isotropic elastic and homogeneous material, it was decided to use a material having such ideal properties. Ciba Geigy 3969 casting epoxy resin mixed with 12% weight of 3269-1 hardener was used. After pouring the mixture in a mould, it was cured for 24 hours at 80° C to remove residual stresses. The epoxy had a Young's modulus of 6.9 Gpa and a Poisson's ratio of 0.37.

The model consisted in a 152 mm diameter by 355 mm long cylinder in which a 38 mm diameter borehole was drilled up to midlength. These dimensions allowed to consider the hole small in comparison with the dimensions of the cylinder which could adequately simulate an infinite medium. A standard doorstopper was used to monitor the borehole bottom strains but its diameter was reduced to 25 mm on a lathe so the stress relief drilling could be done with a 31 mm inner diameter bit. In order to be able to simulate a wide range of loading conditions with a single cylinder, the stress relief drilling process was done by increments of 1 mm at a time, between which the cylinder would be loaded biaxially in a triaxial cell up to a stress of 6.9 Mpa and the axial stress would then be applied gradually up to a stress of 34.5 Mpa, allowing to obtain SR ratios ranging from 0 to 5. During the loading process, the strains were continuously monitored with a multichannel data acquisition system [21]. The strain recovery curves can then be obtained for a wide range of loading conditions by plotting the measured strains as a function of the drill bit advance. Such curves are shown in Figure 12. Figure 13 shows different RPR values for different SR values with the curve obtained from interpolation of the finite element analyses shown as a continuous line. It is seen that the match is very good, even though the results from finite element analyses had to be linearly interpolated between Poisson's ratio of 0.30 and 0.40.

6 - DISCUSSION

From the curves in Figures 8 and 9, it is concluded that the RPR method will have a good accuracy in the SR range comprised between 0 and 4 or 0 and 8, depending if the Poisson's ratio of the rock is close to 0.5 or 0, respectively. This SR range covers most of the possible in situ stress states. For SR values greater than 8, a very small variation in RPR would translate in a high SR variation, making the RPR method inappropriate.

It would be interesting to determine the accuracy with which the stresses can be determined using this technique. In practice, there is no reason why the strains measured during stress relief drilling should not be more accurate than the strains measured prior or after drilling. If the strains are affected by temperature effects, these can be corrected, as already demonstrated. Moreover, the RPR being a ratio, any problem related to bonding effects are compensated as these should influence identically the peak and recovered strains unless the bonding problems occur between the peak and recovered strains. Consequently, the accuracy of the RPR method will be as good as the accuracy on the measured strains, which in turn depends on the quality of the bonding, drilling and on the care taken for all the operations described in the section on modified field procedure.

It should be emphasized that the Poisson's ratio be correctly determined, as the RPR is relatively sensitive to variations in ν. The diametral compression test performed on the recovered core to which the doorstopper cell is bonded [3] is a valuable tool for calculating this parameter, as it is measured at the location where the stresses are to be obtained. The test allows to introduce the influence of anisotropy and can be performed in situ without the need for additional laboratory tests. The methodology described by Corthésy et al. [3] also gives the parameters required for interpreting the measurements.

Contrary to the standard doorstopper cell, the standard borehole deformation gauge (BDG) cells, continuously monitor borehole diameter changes while the overcoring proceeds. In terms of available

information from only one measurement, the BDG, like the conventional doorstopper, only gives a partial 2D stress tensor, as only 3 independent equations are available for four unknowns, these being σ_x, σ_y, τ_{xy} and σ_z. At this time, preliminary finite element analyses were performed to evaluate the potential of the RPR method for borehole deformation gauges. The results are encouraging and the same tendencies are found, although the RPR method does not seem to be as sensitive for this type of gauge as it is for the doorstopper gauge. Further analyses on numerical and physical models are underway, and the results will be available shortly.

Although CSIRO or CSIR triaxial cells give the complete 3D stress tensor from a single borehole measurement, it is believed by the authors, that the RPR method could also be applied to these cells to get extra information allowing a cross check the calculated stresses.

7 - CONCLUSION

The modifications made to the standard doorstopper cell and to the field procedure to allow both strain recording, rock-cell temperature and precision resistor monitoring while stress relief is in progress have been briefly described. The proposed improvements can be done very easily, rapidly and at a relatively low cost. The strain recovery curves give directly the total strains to be fed into the stress calculation models and they can be used directly as a diagnose tool. The modifications to which the present paper refers also allow in situ stress measurements in flooded or wet boreholes [11]. But the main advantage one gets from these strain recovery curves, is that they allow the calculation of four stress components from only one measurement in a single borehole, and the complete 3D stress tensor can be obtained from measurements performed in two non parallel or non perpendicular boreholes. The RPR method is very simple to apply and the laboratory validation it has undergone indicates it is a tool that can be trusted. Field measurements where the RPR method will be compared to more conventional techniques will constitute the ultimate validation test for this method. Moreover, if one wishes to conduct measurements in three boreholes although now, only two are necessary, the extra equations given by the RPR method should be used to increase the quality of the stress calculation.

ACKNOWLEDGEMENTS

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APPENDIX A

Proof that six independent equations can be obtained
from two non parallel, non perpendicular boreholes

APPENDIX A

To demonstrate that only two holes are sufficient to calculate the 3D stress tensor, it is necessary to show that 6 independent equations can be found from the 8 equations available. Let x,y,z and x',y',z' be the reference systems of two non parallel non orthogonal boreholes making an angle β and $90°\text{-}\beta$ between the X axis in the XY plane of the XYZ global coordinate system. Figure 1 illustrates the case analysed. Using the relationships between stresses at a point, the following matrix can be written,

$$
\begin{vmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \sigma_{x'} \\ \sigma_{y'} \\ \sigma_{z'} \\ \tau_{x'y'} \end{vmatrix}
=
\begin{vmatrix}
l_1^2 & m_1^2 & n_1^2 & 2m_1n_1 & 2n_1l_1 & 2l_1m_1 \\
l_2^2 & m_2^2 & n_2^2 & 2m_2n_2 & 2n_2l_2 & 2l_2m_2 \\
l_3^2 & m_3^2 & n_3^2 & 2m_3n_3 & 2n_3l_3 & 2l_3m_3 \\
l_1l_2 & m_1m_2 & n_1n_2 & (m_1n_2+n_1m_2) & (l_1n_2+n_1l_2) & (l_1m_2+m_1l_2) \\
l_1'^2 & m_1'^2 & n_1'^2 & 2m_1'n_1' & 2n_1'l_1' & 2l_1'm_1' \\
l_2'^2 & m_2'^2 & n_2'^2 & 2m_2'n_2' & 2n_2'l_2' & 2l_2'm_2' \\
l_3'^2 & m_3'^2 & n_3'^2 & 2m_3'n_3' & 2n_3'l_3' & 2l_3'm_3' \\
l_1'l_2' & m_1'm_2' & n_1'n_2' & (m_1'n_2'+n_1'm_2') & (l_1'n_2'+n_1'l_2') & (l_1'm_2'+m_1'l_2')
\end{vmatrix}
*
\begin{vmatrix} \sigma_X \\ \sigma_Y \\ \sigma_Z \\ \tau_{XY} \\ \tau_{XZ} \\ \tau_{YZ} \end{vmatrix}
$$

where l_i, m_i, n_i, l_i', m_i', n_i' (i = 1 to 3) are respectively the director cosines in the xyz and x'y'z' reference systems. They are given by the following relationships:

$$l_1 = -\sin\beta \quad m_1 = \cos\beta \quad n_1 = 0$$
$$l_2 = -\cos\beta \quad m_2 = -\sin\beta \quad n_2 = 0$$
$$l_3 = 0 \quad\quad m_3 = 0 \quad\quad n_3 = 1$$

for the l'_i, m'_i, n'_i director cosines, angle β is replaced by β'.

Replacing the director cosines by their value for given borehole orientations allows to build a matrix, that once in echelon form, is a rank 6 matrix, proving that 6 independent equations are available if the angle between the two boreholes is different from $0°$ or $90°$. For the $0°$ angle four independent equations are available whereas for the $90°$ case, 5 independent equations are available, which is insufficient to determine the 3D stress tensor. Any angle in between will allow the calculation of the 3D stress tensor.
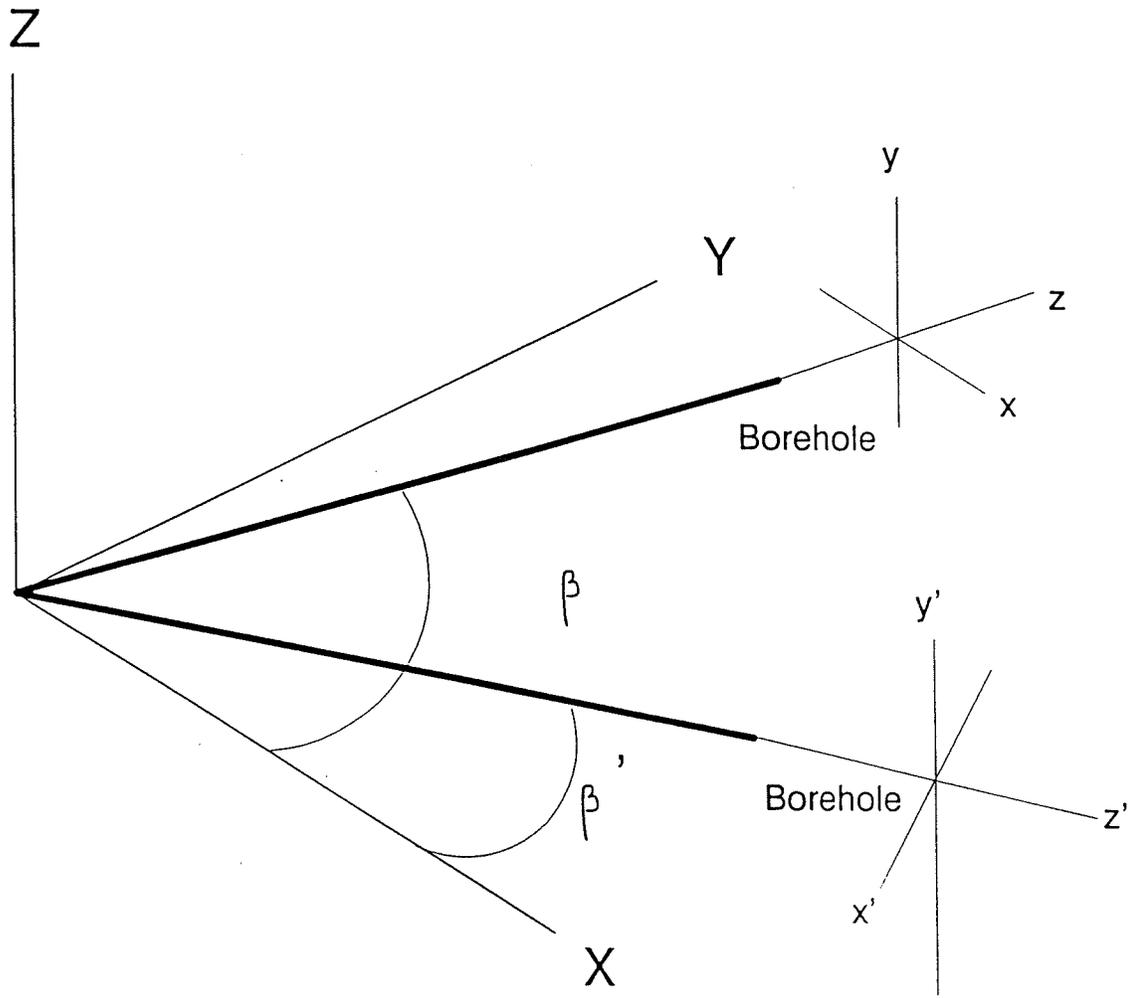
Figure 1:   Global and borehole reference systems
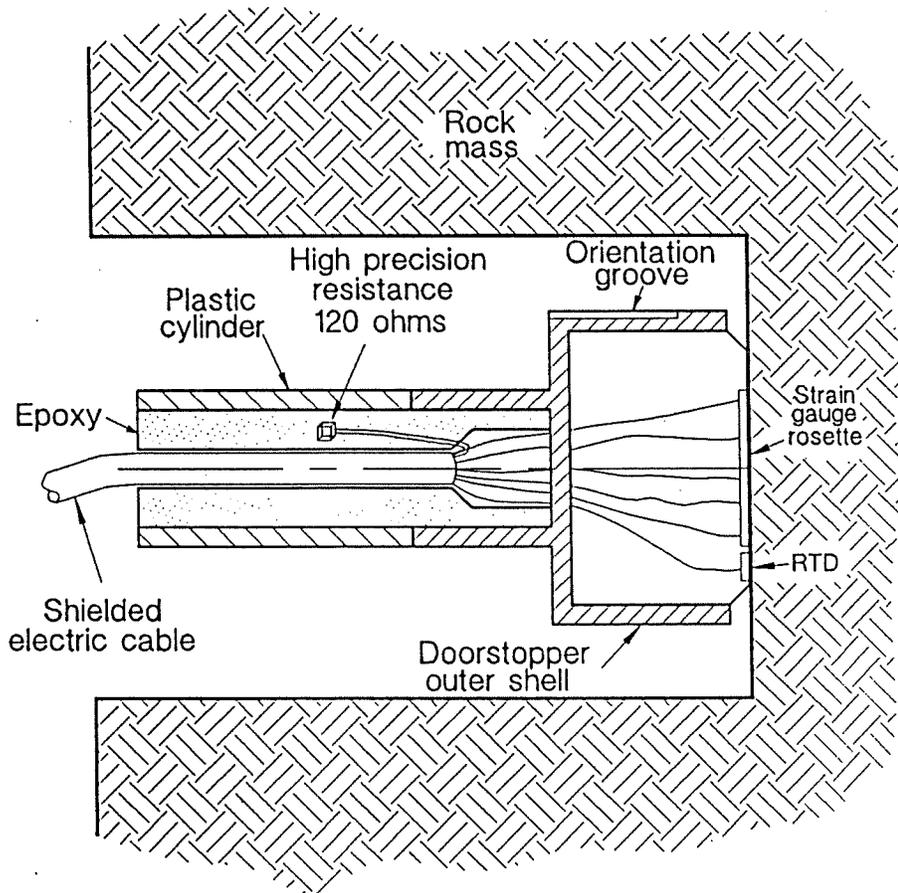
Figure 2:   Modified doorstopper cell
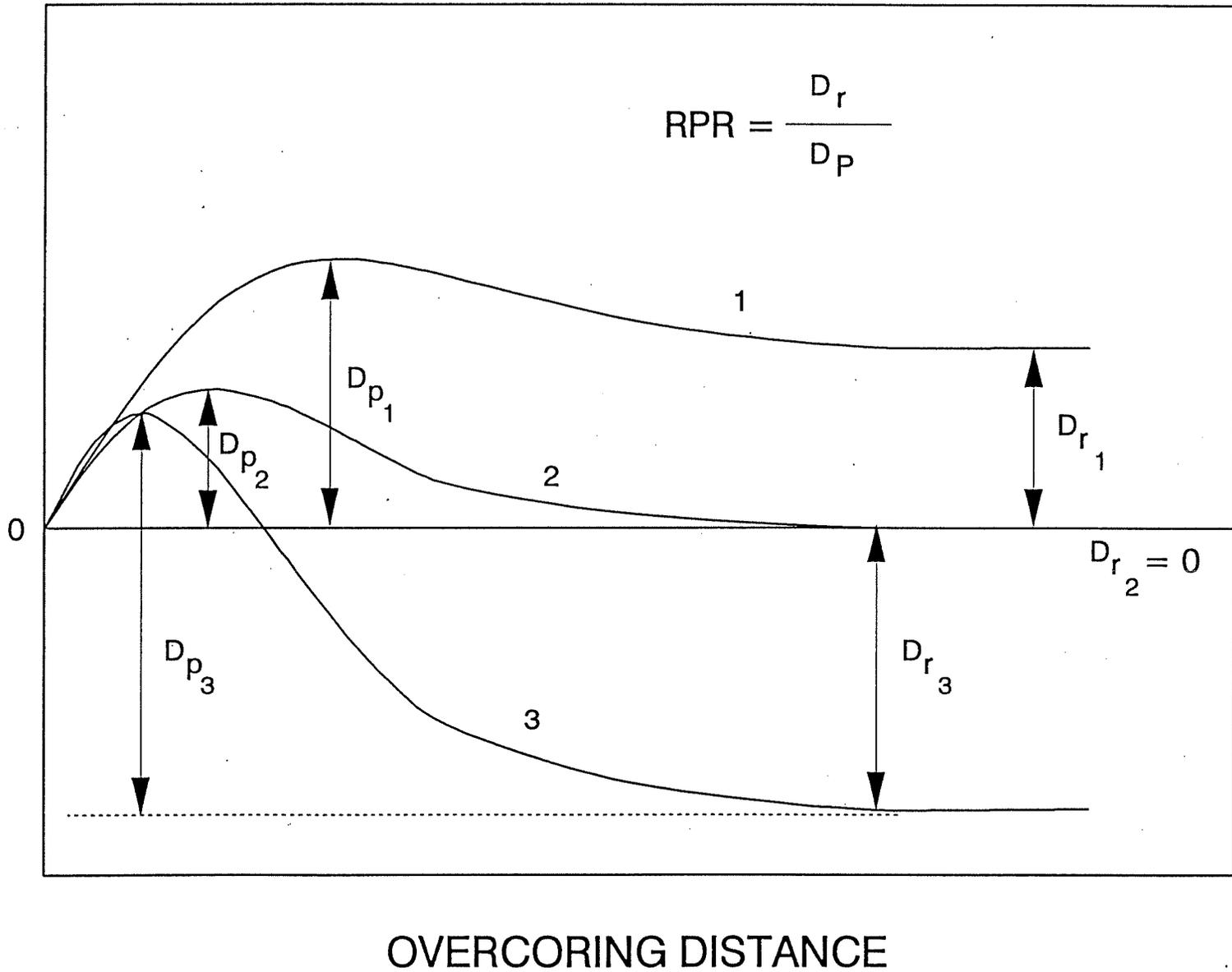
Figure 3:   Method for calculating the RPR

Lin-STRESS Lc=15
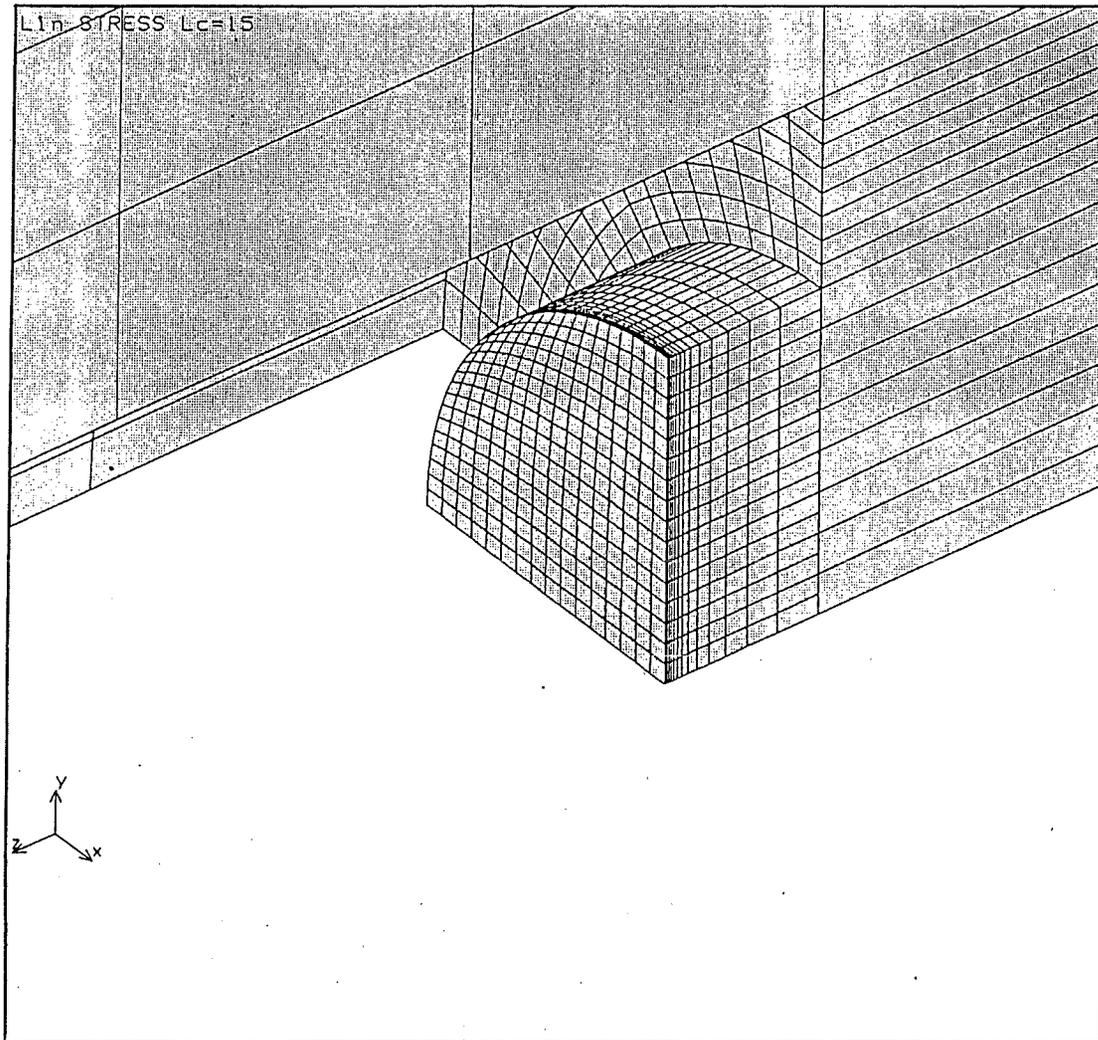
Figure 4:   Detail of the 3D mesh used in the finite element analyses

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Version V1.65A
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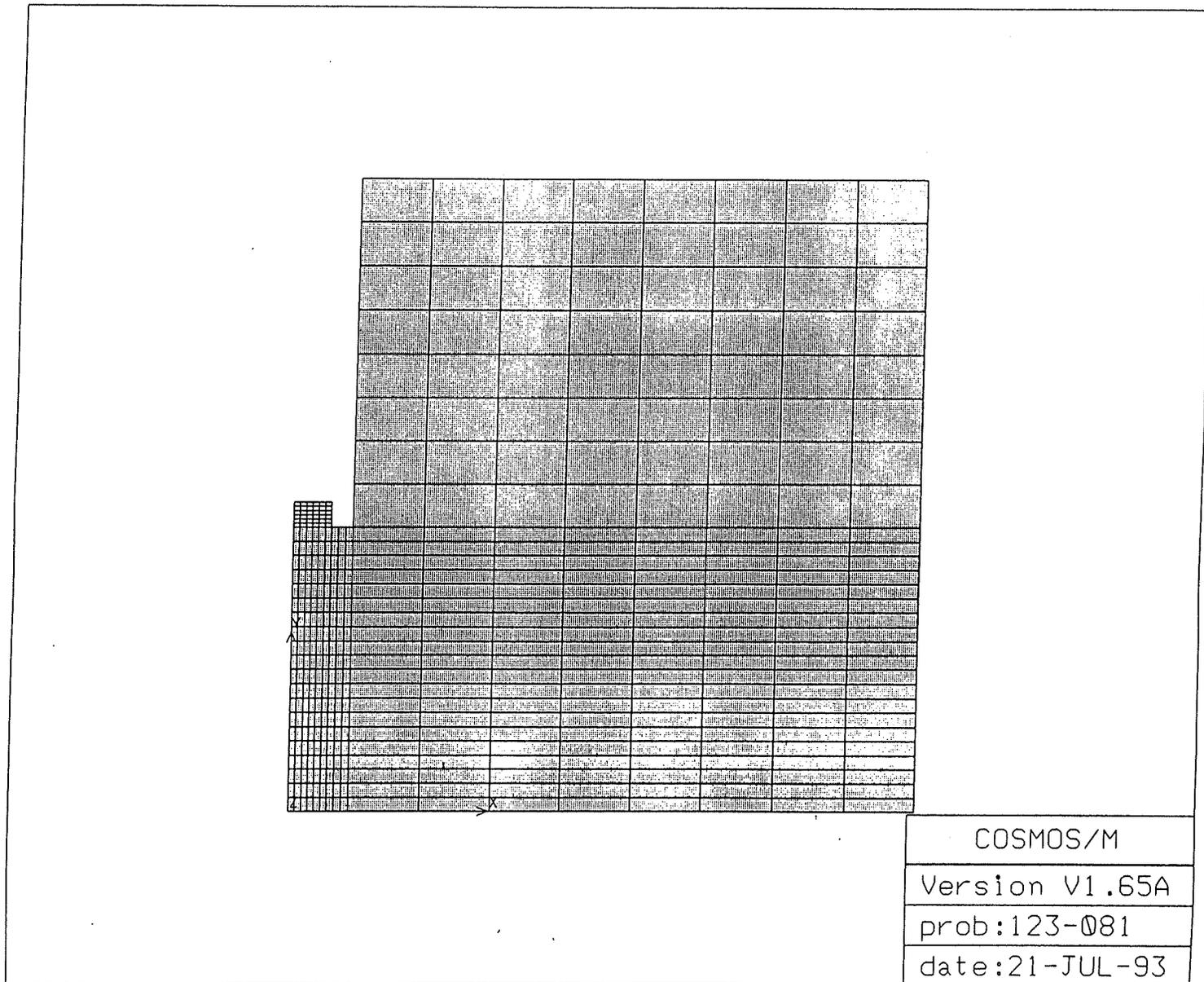
Figure 5:   Mesh used for the axisymmetric finite element analyses
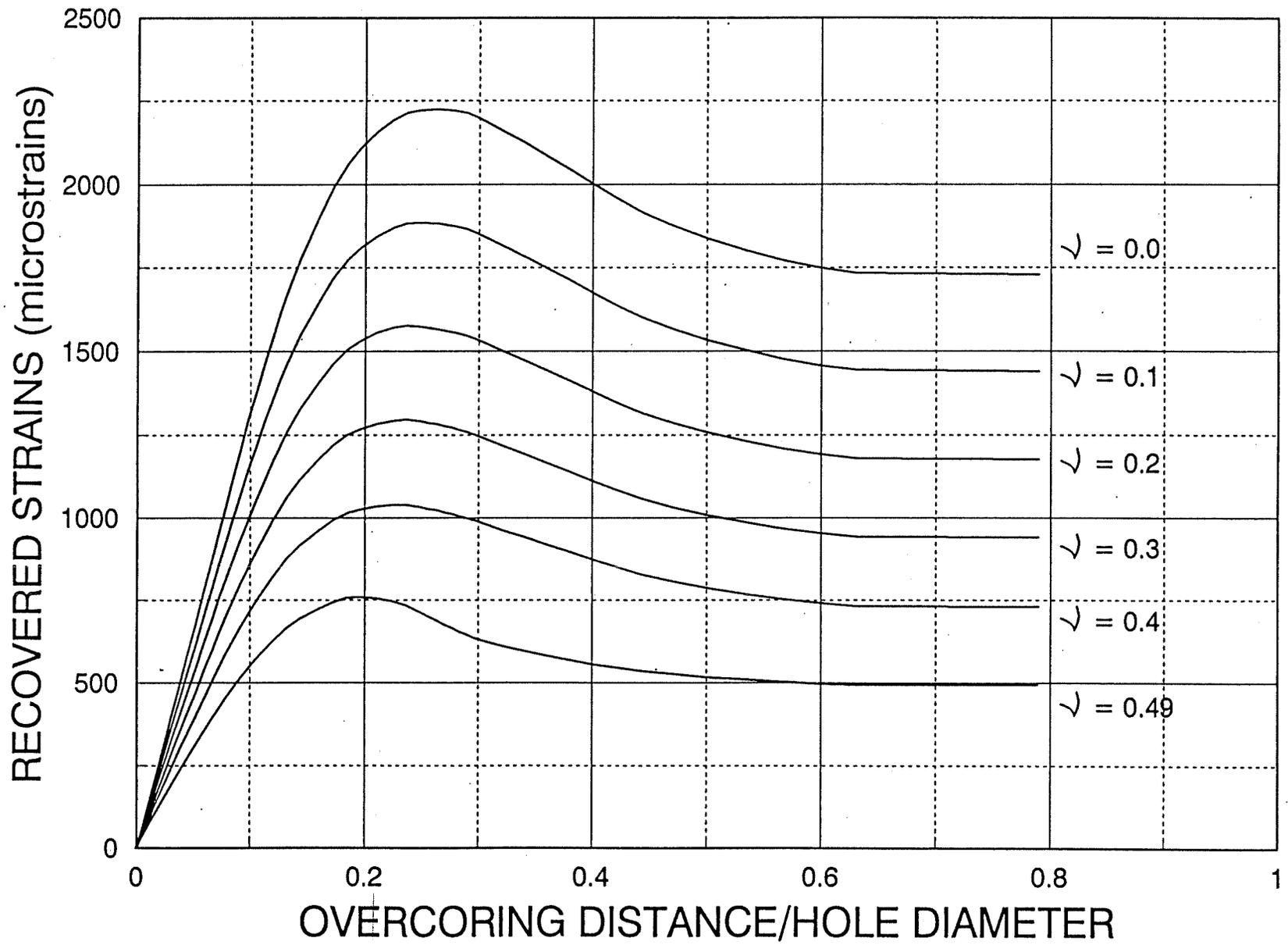
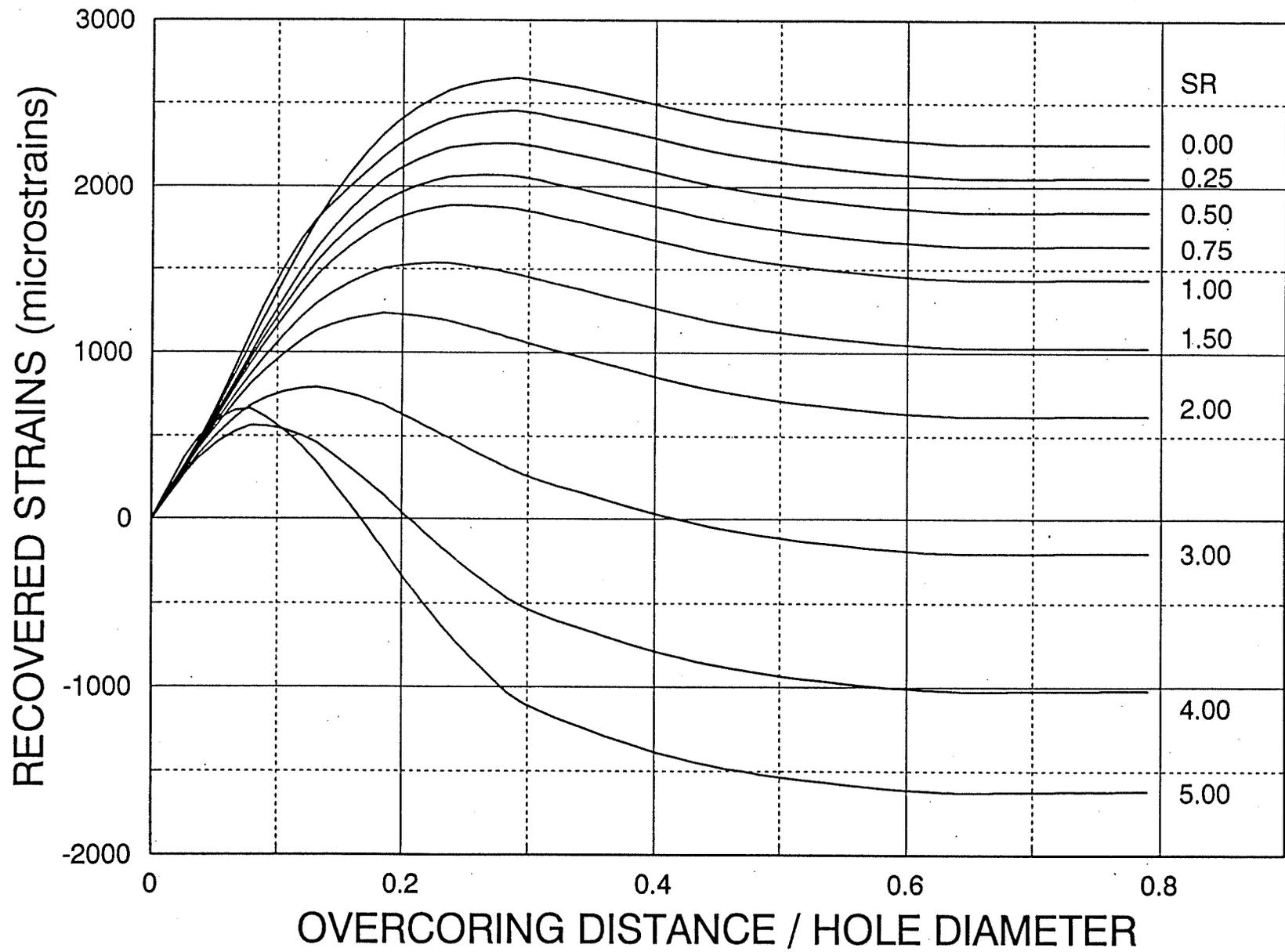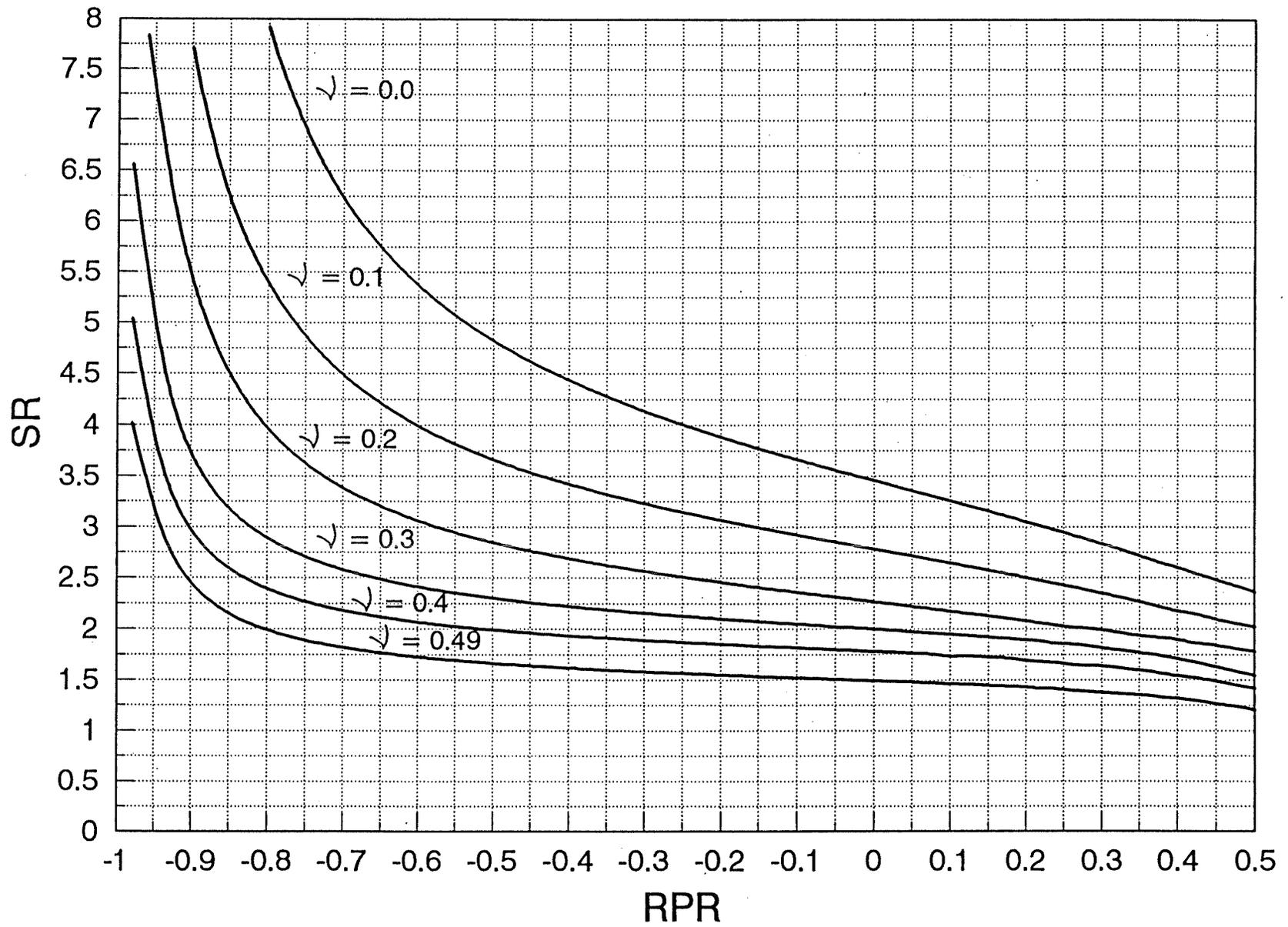Figure 6:   Strain recovery curves for different Poisson's ratios

Figure 7: Strain recovery curves for different SR

Figure 8:   RPR-SR relationships for SR > 2
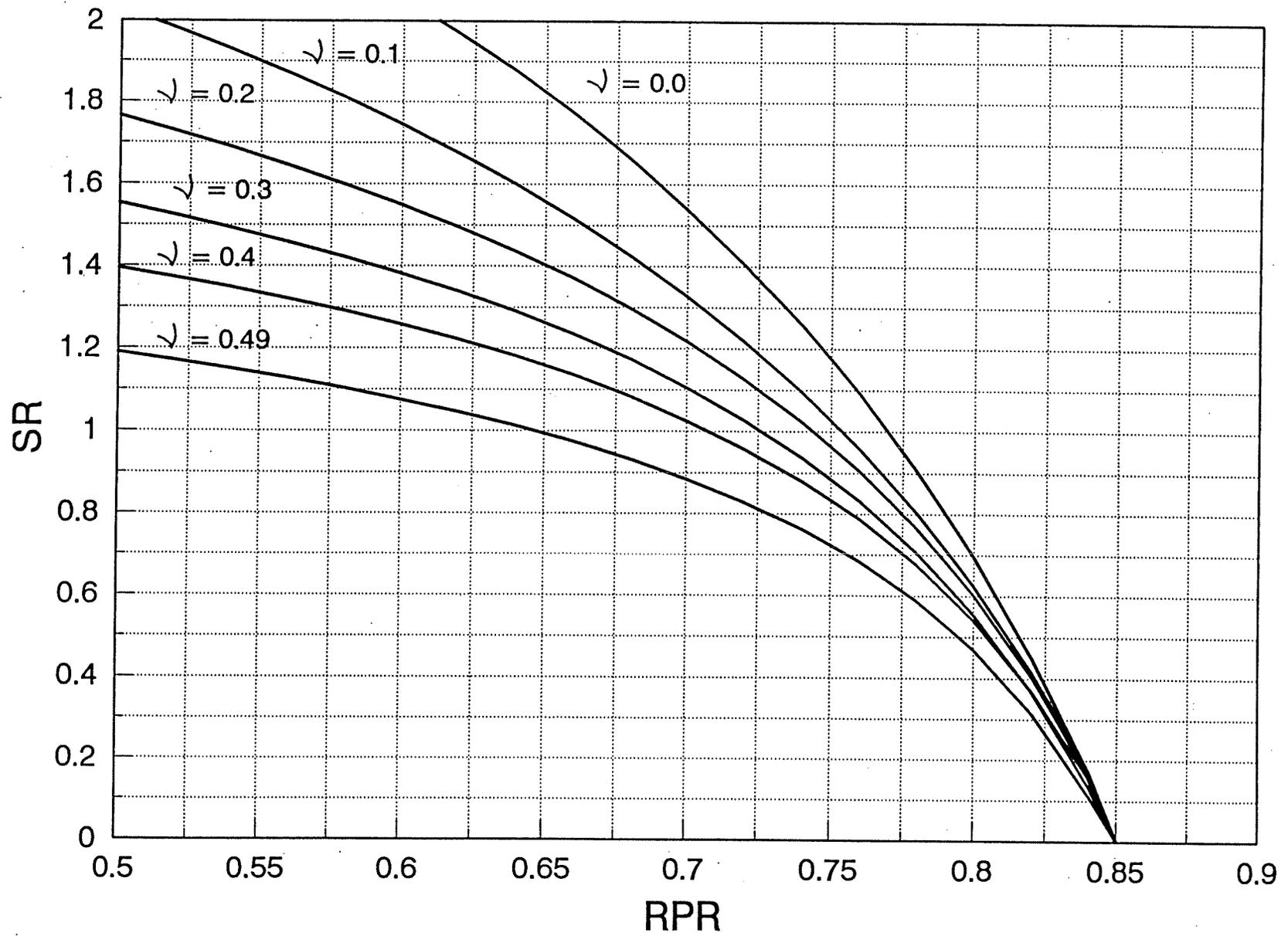
Figure 9:   RPR-SR relationships for $0 \leq SR \leq 2$
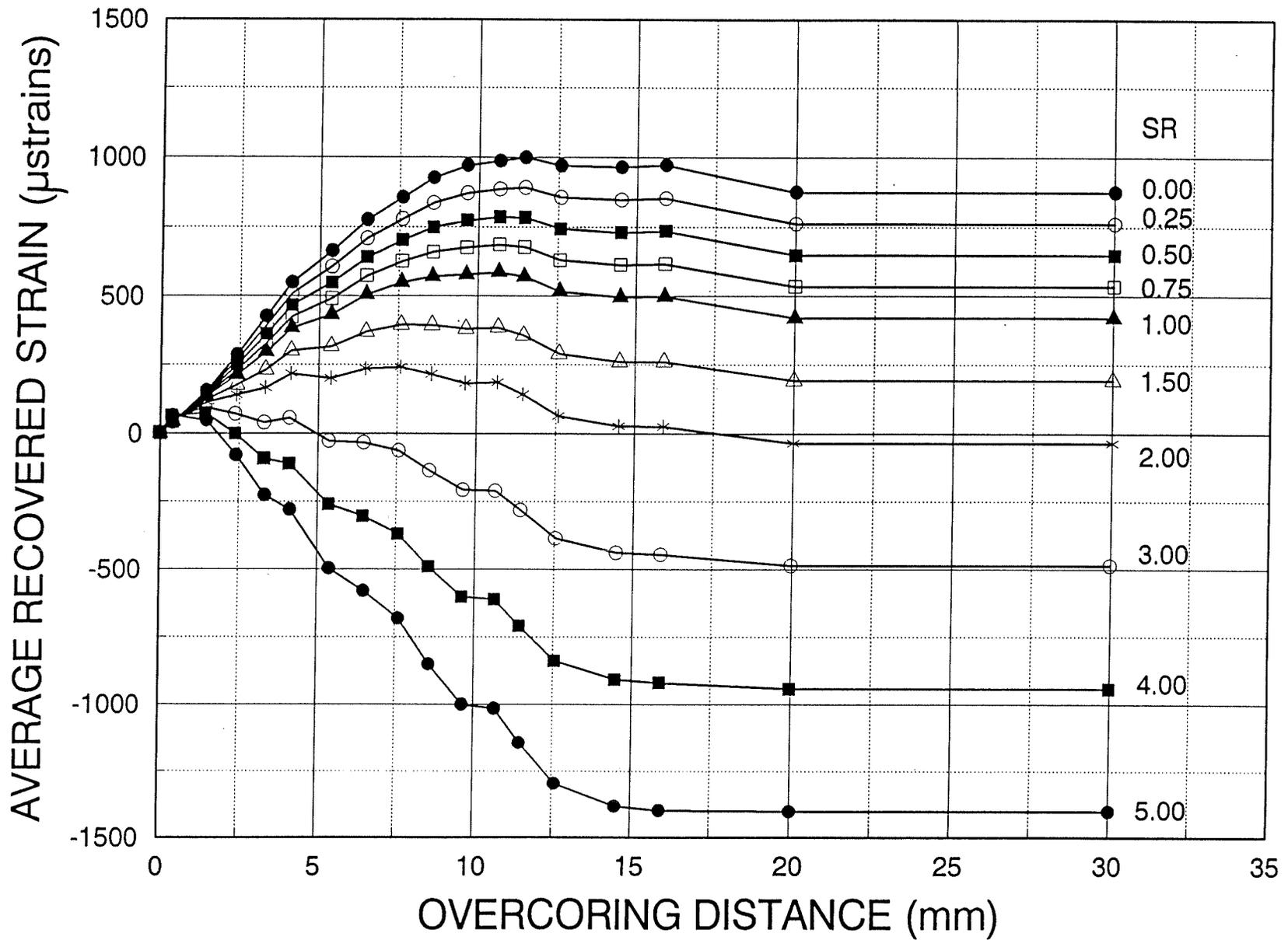
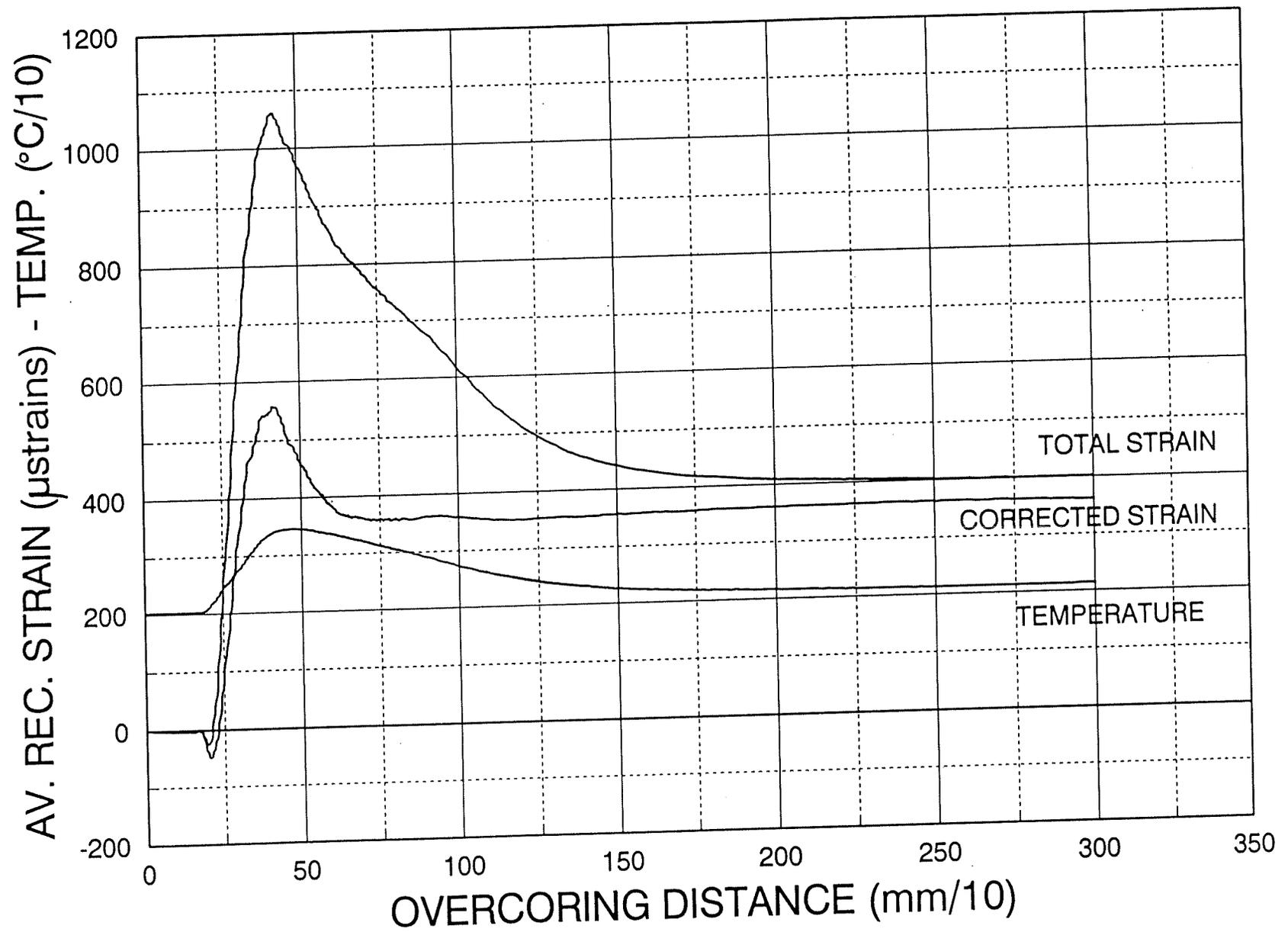Figure 12: Strain recovery curves from laboratory stress measurement simulations on an epoxy cylinder

Figure 11:   Strain recovery curves from laboratory stress measurement simulations on a rocksalt cylinder (from Corthésy and Gill, 1990)
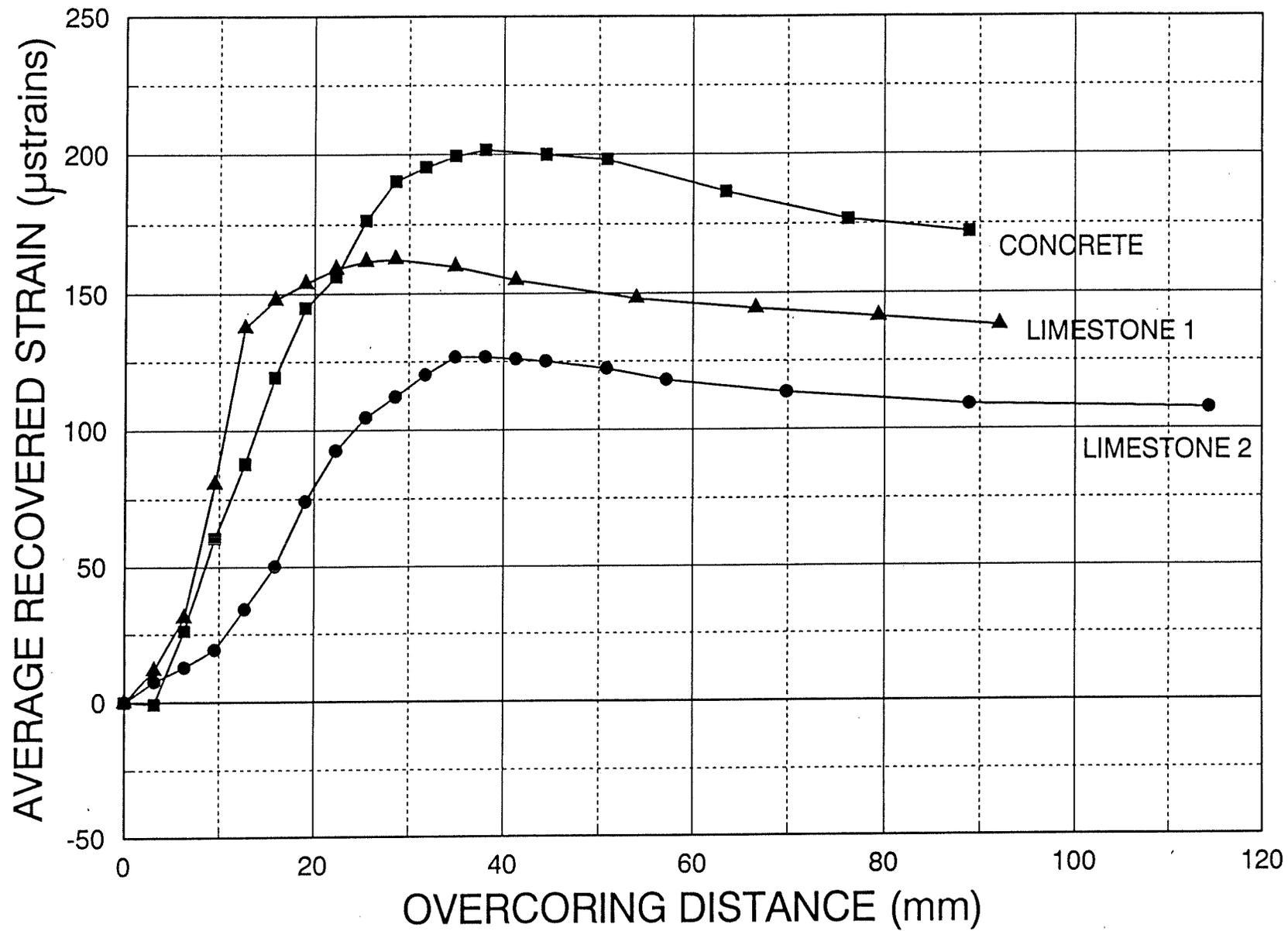
Figure 10: Strain recovery curves from laboratory stress measurement simulations on limestone and concrete blocks (from Fortin, 1981)
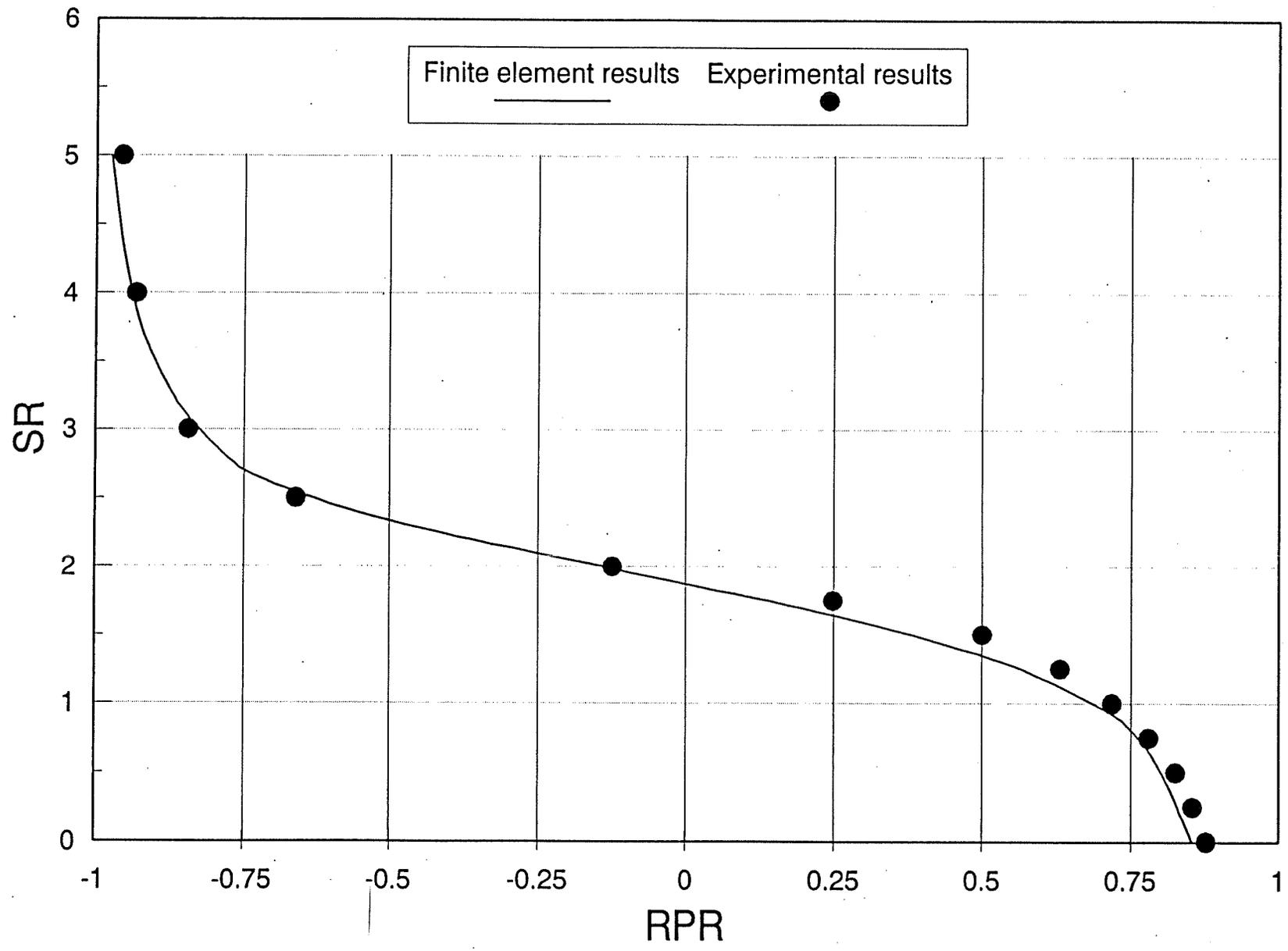
Figure 13: Comparison of the RPR-SR relationships from finite element analyses and stress measurement simulations on an epoxy cylinder