DIFFERENTIAL STRAIN ANALYSIS: AN INVESTIGATION OVER ITS FEASIBILITY FOR DETERMINING COAL'S CLEAT ORIENTATION

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ABSTRACT

Gas production from coal bed methane (CBM) has been rising as supplement to conventional gas reservoirs. Effective CBM production is much determined by well placements with regards to orientation of the coal reservoir's face cleat. This is true since this cleat type provides the main path of fluid migration from storage to wellbore. It is therefore imperative to understand and determine the general orientation of the cleats of concern. This information is usually obtained from visual description on core samples, and whenever available from analogy to outcrop data. This is considered as insufficient and a means for studying core sample's interior is required in order to ensure consistency between external and internal appearances. This paper presents an investigative study over the possibility of differential strain analysis (DSA) technique to serve the purpose. The technique is normally used for measuring subsurface in situ stress field, and through the use of a similar basic concept it is proposed to be used for determining orientation of face cleats in coal samples. The study includes utilization of DSA data obtained from measurements on samples taken from great depths. Review and re-working over the data has shown that the technique can well indicate the orientation of face cleats. A general orientation over all tested samples is also indicated with reasonable degree of reliability. This leads into conclusion that the DSA technique can be well used to indicate cleat orientation and therefore help in better characterizing coal.

Key words: *Coal, cleats, coal bed methane, effective production, cleat orientation, differential strain analysis, core samples, better coal characterization.*

I. INTRODUCTION

Exploitation of coal bed methane (CBM) operates under different mechanisms than those prevailing in conventional gas sand reservoirs. The important mechanisms that characterize coal formations include physical structure, adsorption/desorption mechanism, flow mechanism (Darcy flow and diffusion), and two-phase flow (Ahmed et al, 1991). Those four important mechanisms nonetheless govern storage and flow mechanism in coal. As put by various sources, such as Saghafi (2001) and Karimi (2005), coal contains porosity but very little matrix permeability. In order for fluids to be produced out of coal seam to production wells, the coal must have an extra system for secondary permeability such as fractures. These fractures, commonly termed as cleat, allow water, gases, and other fluids to migrate from matrix towards the wells. Cleat system represents network of natural fractures that exists in coal as part of its maturation process.

Cleats were generated as results mainly of dehydration and regional stresses. Cleats largely control the directional permeability of coals, and therefore, are very important for CBM production through optimum well placement and spacing. Efficient and effective well placement could further be enhanced by inducing carefully-designed hydraulic fractures that link a great number of these cleats directly to the wells and improve production (e.g. Stewart and Barro, 1982). Understandably, knowledge over orientations of the cleat sets is utterly desired.

Description over the cleats and determination of their general orientation can be performed using some means including direct observation on oriented cores (cores having azimuth reference given and marked on them during coring using a special subsurface device) such as direct visual description and *computerized tomography* (CT) scanning, direct survey using borehole wall imager logging, and if condition permits analogy to outcrops. This paper offers an alternative technique, *differential strain analysis* (DSA).

The DSA technique was originally established for examining discontinuities in the interior of rocks and later was used for determining subsurface *in situ* stress fields. A study was then carried out to investigate the possibility of using this technique for determining coal cleat system's orientation, and the results are summarized and presented in this paper. It is hoped that through the use of this less direct method, a different angle of view is obtained hence enriching one's conclusion on the needed coal's cleat characterization. As put by Jenkins et al. (2002), thorough description and evaluation on coal core samples help much in characterizing coal reservoirs.

II. DIFFERENTIAL STRAIN ANALYSIS

Differential Strain Analysis (DSA) is basically a technique for measuring strain (deformation caused by application of stress, presented in form of fraction relative to the medium's original dimension, ε) of a rock specimen as a function of hydrostatic confining pressure. DSA was initially developed by Simmons et al. (1974). It was initially established for examining cracks within rocks (e.g. Siegfried and Simmons, 1978) as well as for studying rock's past history (e.g. Batzle and Simmons, 1976). Recognising the existence of stress-relieved microcracks in core samples derived from oil and gas wells Strickland and Ren (1980) and Ren and Roegiers (1983) further developed the technique for measuring earth's *in situ* stresses at great depths. Later Dyke (1988) and Widarsono (1996) successfully utilized the technique for measuring *in situ* stresses in some parts of North Sea.

In DSA technique, a tested rock specimen is subjected to externally-applied hydrostatic pressure. Upon loading, the cracks (or microcracks) possibly present in the specimen will close as a reaction against the hydrostatic pressure. The incremental closure of these cracks under increasing pressure transforms the specimen from a discontinuous to continuous state, hence modifying the stress-strain response. The stress-strain relationship for the hydrostatically stressed rock is given by (Walsh, 1965):

$$\Delta V = \frac{3(1-2\nu)}{E} P + \eta(P) \quad (1)$$

where ΔV is the change in volume of the rock specimen, ν is Poisson's ratio, E is Young's modulus, P is hydrostatic pressure, and $\eta(P)$ is crack porosity. The first term in Eq. 1 represents the intrinsic elastic behaviour of the specimen considering the cracks non-existence, and the second term represents the contribution of the closing cracks (and microcracks). Graphically, the relationship is illustrated in Figure 1. The zero-pressure intercept, η_o , is the total volume of racks present in the specimen. This value is achieved when the critical pressure, P_c , at which all cracks are closed has been reached. Theoretically, at pressures higher than P_c the rock behaves elastically.

In practice, ΔV is obtained from the summation of three normal strains recorded in three principal directions (see Figure 2). However, in characterizing

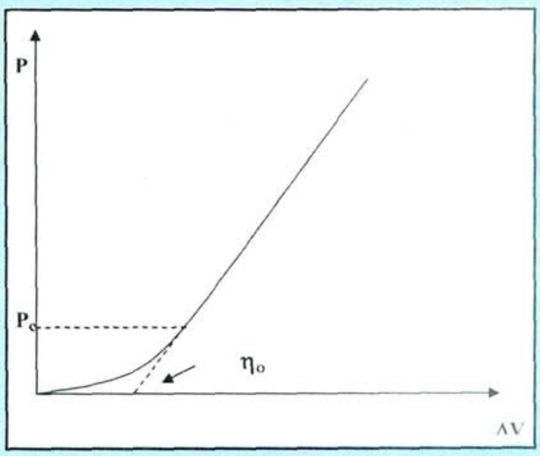

Figure 1
Stress-strain relationship of hydrostatically stressed rock specimen

the cracks, only the strains due to their closure are desired. This can be taken as in Figure 1. Then is the summation of in the three principal direction of the measurement.

A. *DSA for in situ stress determination*

In using DSA for determining *in situ* stress orientation and magnitude (Strickland and Ren, 1980), ΔV is not the main concern. Instead, it is the direction of the largest that is desired since it represents the direction of the highest stress-relieved microcrack (microcracks generated in core samples as results of sudden stress removal during the core's retrieval in wellbore) density. Direction of highest microcrack density does not necessarily fall in the principal directions of the test specimen. It could fall in any directions oblique to the three principal directions. It is DSA's main purpose to find the largest from the strain data obtained from measurements.

A set of DSA data obtained from strain gauge recording (see Figure 2) provides a set of strains, normally ascribed as ε_x, ε_y, ε_z, ε_{xy}, ε_{xz}, and ε_{yz}. Using stress tensor analysis (see Jaeger and Cook, 1978 for instance), the strain ε may be described using *direction cosines* (l, m, n) with *angles* (, ,) with respect to the three principal axis (OX, OY, and OZ in Figure 2), by the following equation:

(2)

The direction cosines are connected by a relation:

$$l^2 + m^2 + n^2 = 1 \qquad (3)$$

When the normal strain across a plane is either a maximum or a minimum, the shear stress across the plane is zero. If ε is the unknown value of the normal strain across this plane, the relationships become:

(4)

$$l\varepsilon_{xy} + m(\varepsilon_y - \varepsilon) + n\varepsilon_{zx} = 0 \qquad (5)$$

$$l\varepsilon_{xz} + m\varepsilon_{yz} + n(\varepsilon_z - \varepsilon) = 0 \qquad (6)$$

$$\varepsilon_x = l\varepsilon$$

$$\varepsilon_y = m\varepsilon \qquad (7)$$

$$\varepsilon_z = n\varepsilon$$

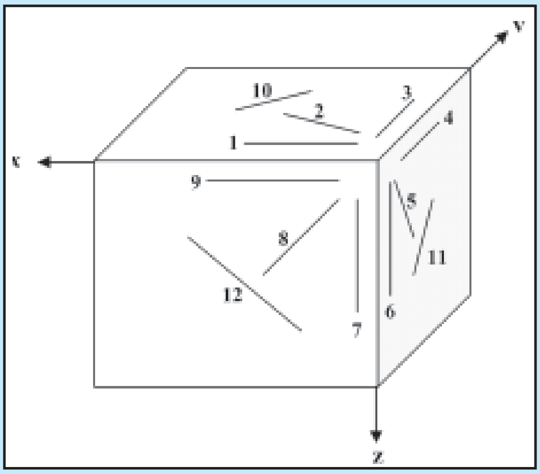

Figure 2
Arrangement of strain gauges and the three principal directions x, y, and z in the test rock specimen

The roots of the three Equations 4, 5, and 6 are real, ε_1, ε_2, and ε_3. These are the *principal strains*. Solving any two of the three equations results in a set of direction cosines (l_1, m_1, n_1) that corresponds to ε_1. In a similar manner, ε_2 and ε_3 are associated with (l_2, m_2, n_2) and (l_3, m_3, n_3), respectively. Using these three mutually perpendicular sets of direction cosines sets of direction angles ($\alpha_1, \beta_1, \gamma_1$), ($\alpha_2, \beta_2, \gamma_2$), and ($\alpha_3$, , γ_3) can be produced. As orientation of the three principal axis of OX, OY, and OZ are known, the true orientations of the principal strains can consequently be determined.

In the DSA technique for determining *in situ* stress field these principal strains represent the three *principal stresses*, namely major stress, intermediate stress, and minor stress. This is based on the basic presumption that all microcracks in rock samples derived from oil and gas wells are stress-relieved in nature (Strickland and Ren, 1980). For further information regarding stress-relieved microcracking mechanism see Charlez et al. (1986) and Lawn (1993). Ren and Roegiers (1983), Dyke (1988), and Widarsono (1996) present examples of DSA application for determination of *in situ* stress field.

B. *DSA for cleat characterization*

Coal is always fractured, with regularly and closely spaced fractures commonly known as *cleats*. There are two known kind of cleats, *face cleat* and *butt cleat*, apart from *tertiary cleat* (largely un-ori-

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ented micro fractures that terminates in face or butt cleats, as quoted by Karimi, 2005), joints, and faults. The last two types of discontinuities are normally present at larger (seam or reservoir) scales. Face cleats are usually continuous and act as the main channels for flow in coal. Butt cleats are typically oriented perpendicular to a face cleat, smaller and shorter, and are regarded as subordinate to face cleats (Koenig, 1989; 1991). Figure 3 presents a view of cleat system in coal. Readers can see various references (e.g. Close, 1993 and Laubach et al. 1998) for information regarding cleats system, origin, and characteristics.

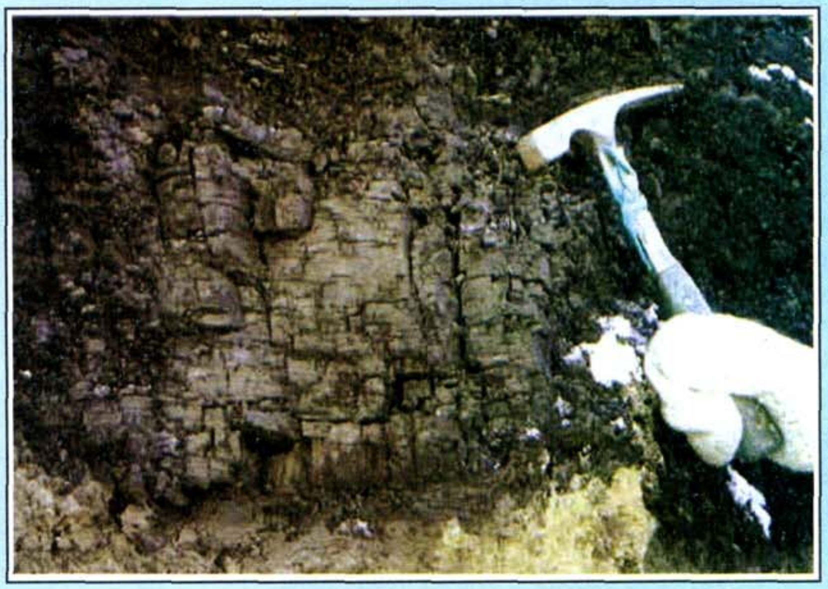

Figure 3
Cleat system in coal. (source: Alberta Geological Survey)

In fact, flow through coal proceeds much faster through face cleats than through butt cleats and this usually result in permeability anisotropy resulting in gas flows mostly in the horizontal direction (elliptical drainage, Koenig, 1989; 1991), with negligible vertical permeability most probably represented by the un-oriented microcracks described by Karimi (2005) as the randomly-oriented tertiary cleats. This implies the existence of three mutually perpendicular permeability systems; the major or main system played by the face cleats, intermediate or medium system represented by the butt cleats, and minor system occuring in vertical direction. The presence of three permeability paths draws an analogy to the concept of three mutually perpendicular stress-relieved microcrack sets, representing the three mutually perpendicular principal *in situ* stresses that underlie the use of DSA for measuring *in situ* stress fields.

For coals, the presumption of stess-relieved microcracks' presence is likely to be overshadowed by presence of the cleats. In other words, ΔV of the cleat system is likely to be far larger than ΔV of the stress-relieved microcracks. This difference may be further widened by CBM reservoirs' relative shallow depths that, despite coal's brittle behaviour, do not allow occurrence of large stress relief. The presumably negligible presence stress-relieved microcracks can therefore be used as a basic postulate that all non-elastic behaviour in coal under hydrostatic pressure is caused by cleats. Consequently, any yielded ε_x ε_x and ε_x can be regarded as indicators of densities of face cleats, butt cleats, and tertiary cracks in vertical direction. The orientations of the cleat sets are simply perpendicular to those directions of cleat densities. Figure 4 helps to illustrate cleats and their density and orientation. This concept is indeed the main thrust of the study presented in this paper, the use of DSA for determining cleats (notably the face cleats) general orientation.

III. LABORATORY INVESTIGATION

In Widarsono (1996), a series of differential strain analysis measurements were made on some wellbore-derived coal samples. The measurements were initially aimed at determining *in situ* stress field prevailing prior to the withdrawal of the core samples from great depths. Differently to results from successful measurements on sandstone and siltstone specimens, measurements on coal samples proved unsuccessful. The failure was much caused by the existing cleats in the specimens, which hydraulically-stressed strains overshadowed strains yielded by any possible presence of *in situ* stress-relieved microcracks. It was a failure but it is now thought that this data is still of any use in relation to this study.

Five bituminous coal specimens were taken from different depths (2555 – 2573 mss) of a vertical production well in the southern part of North Sea. The core samples from which the specimens were taken are oriented in nature. As commonly practiced, the direction of North was used as reference. The coal samples were black, weak, and exhibited the usual presence of a cleat system. However, unlike coals from closer to surface, the core samples did not show, in general, a high degree of major cleat network. It is under this circumstance that the DSA was applied on the samples.

In brief, preparation activities for the specimens included: 1) cubic specimens cutting from the oriented coal cores with y-axis (Figure 2) in direction of the North, 2) attachment of twelve wired strain gauges in an arrangement shown in Figure 2, 3) encapsulation of the wired-up specimen using silicon rubber, 4) calibration of data acquisition system, 5) wire connection of encapsulated specimen to data logger and computer, 6) placement of the encapsulated and wired specimen in pressure chamber, 7) application of hydrostatic pressure and strain measurement. Figure 5 exhibits the layout of DSA system. During each measurement, each specimen set was put under elevated pressure steps of up to maximum pressure of 13,000 psi (89.6 MPa) while electric resistance changes in quarter bridges were scanned by data logger regularly and the corresponding strain values sent to computer for storage and analysis.

Figure 6 presents an example of the pressure – strain behaviour of coal specimens (specimen #1). In the figures (a and b) six representative curves from six gauges are plotted. Note that from the twelve gauges only six strains (, , , ε_{xy} , ε_{xz} , and ε_{yz}) are actually needed for analysis. This means only strains from gauges #1, #3, #6, #2, #8, and #5

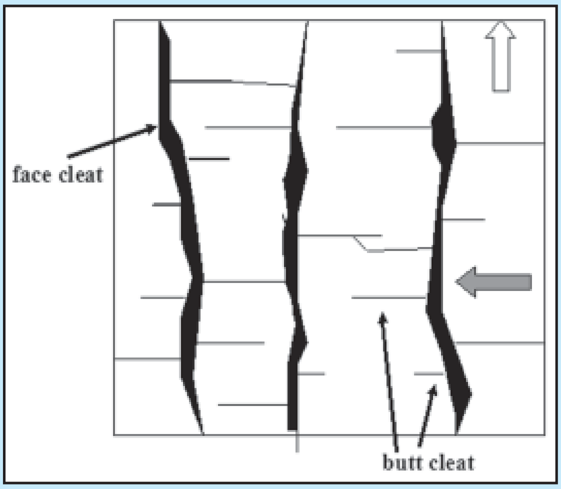

Figure 4
Idealized and simplified illustration of coal's cleat system in vertical direction. Face cleats provide main source of the coal's permeability due to their large opening (i.e. large closing strain under hydrostatic pressure) while butt cleats are oriented generally perpendicular to face cleats. Notice the possible role of butt cleats as interconnectors between face cleats. White arrow indicates orientation of the face cleat set and dark arrow represents its corresponding direction of cleat density.

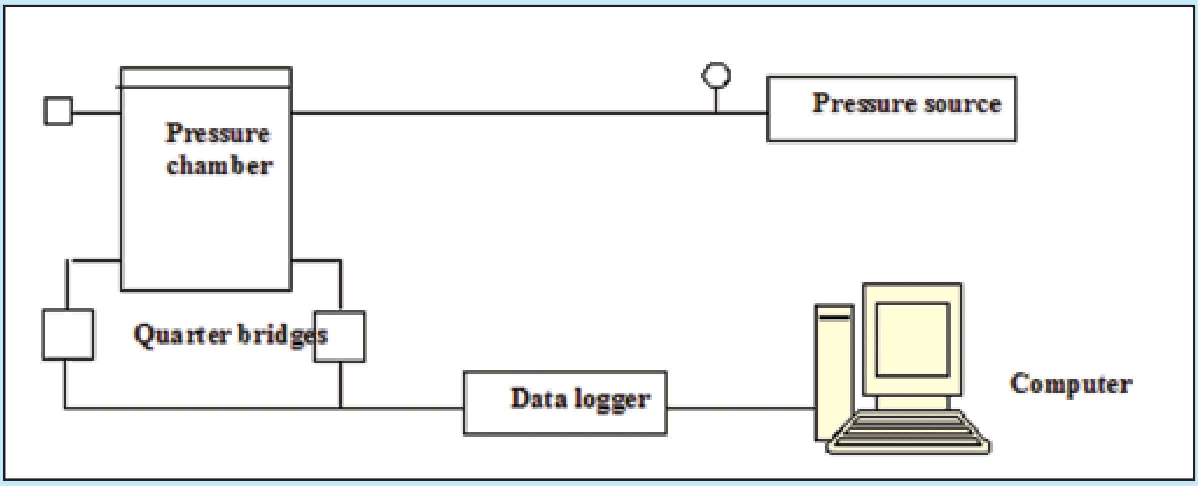

Figure 5
Layout of DSA system

(or gauges #9, #4, #7, #10, #12, and #11, respectively) are needed. The two sets of strain data are interchangeable in case of faulty gauge(s) encountered during measurement. In case of two interchangeable gauges working properly, average values between the two were adopted. In case of two faulty interchangeable gauges was encountered serious problem may occur in the stress/strain tensor analysis. Re-test or a careful examination has to be spent before replacing the failed gauge(s) with synthetic data or data taken from other gauges.

From Figure 6, it can be observed that each compression curve of specimen #1 follows a compression pattern shown in Figure 1. It has two slopes with a 'transition' region in between. The slope (of the lower roughly straight-line) represents the behaviour of discontinuities (in this case are assumed as cleats) closure under hydrostatic compression, whereas the upper slope (of the straight-line) represents intrinsic/cleat free compression behaviour of the coal. The presence of inter-slope transition can be explained in two ways. First, it exists as a result of strains due to the closure of the randomly oriented microcracks like the tertiary cleats, as previously described. Second, it is present as a result of closure of part of the cleats (face cleats or butt cleats) that have non-uniform opening sizes. It serves as a testimony that none in the nature is completely uniform.

In general, data for the five oriented specimens managed to be prepared for analysis, even though data of some gauges needs replacement due to gauge failures. Table 1 presents list of data availability for the five samples. Among the five specimen sets, it appears that specimens #1 and #3 have the most reliable data with complete data availability to all six strains required for establishing a strain tensor for DSA. In the other hand, specimen #4 has the least reliable data since its two pairs of interchangeable gauges failed and replacement was needed accord-

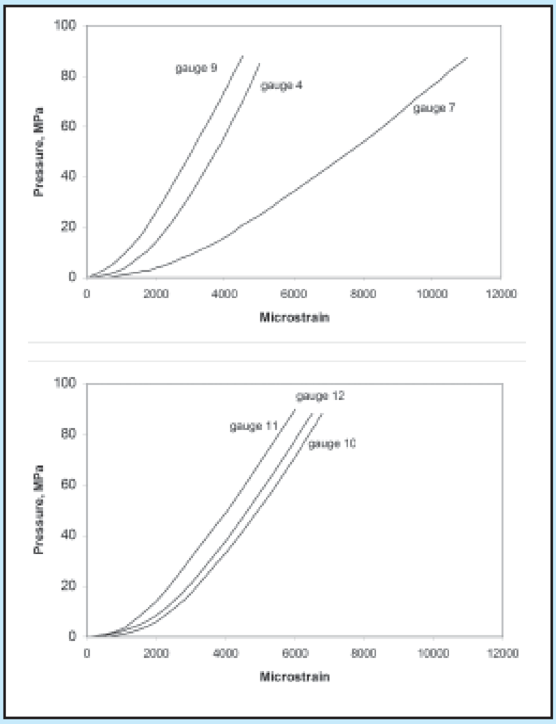

Figure 6
Pressure – strain behaviour of specimen #1 coal. Representative data from gauge nos: a) 4, 7, and 9, and b) 10, 11, and 12.
(source: Widarsono, 1996)

Table 1
Data availability for strain tensor required by DSA analysis

Specimen	Gauge no. for						Remark
	ε_x	ε_y	ε_z	ε_{xy}	ε_{xz}	ε_{yz}	
#1	avg	4	avg	avg	12	avg	no replaced gauge
#2	avg	3	7	2	12	repl	repl gauge no.: 7
#3	avg	avg	avg	2	avg	avg	only gauge no. 10 failed
#4	repl	3	repl	10	8	11	repl gauge nos.: 8 & 11 for e_x & e_z
#5	9	avg	repl	avg	avg	5	repl gauge no.: 8

Note: avg: averaged between two interchangeable strains
repl: both interchangeable gauges failed, replaced by data from other gauge

ingly. Since re-test was almost impossible – it was feared that the coal specimens might crumble when the encapsulation was opened – selection over replacement gauges were made in a very careful manner. First priority was given to the closest strain gauges and they must not cross surface features that are different to the ones crossed by the faulty gauges. Although DSA is essentially a technique for characterizing discontinuities within the specimens, it is hoped that the observation may reduce error in the results.

IV. DATA ANALYSIS

In DSA for determination of *in situ* stress some additional data is required, including: orientation of reference line, overburden stress, pore pressure, and Poisson's ratio. The orientation of reference line (the North direction) is required for determining the true orientation of the three principal stresses *in situ* stress field. The remaining data is actually required for estimating magnitudes of the resulting stresses. In the use of DSA for determining cleat orientations, it is only the orientation of reference line needed. Nevertheless, since the data for this study is derived from Widarsono (1996), in which the end results of computer program used were major, intermediate, and minor principal *in situ* stresses, then the orientations of face cleats, butt cleats, and the vertical permeability are simply taken as perpendicular to those stresses.

The compression data was analysed using the stress tensor analysis method as suggested by Strickland and Ren (1980), and is described earlier. The results are ratios of principal strains, $\varepsilon_1 : \varepsilon_2 : \varepsilon_3$. Ignore the next step of converting these principal strains to principal stresses as performed in Widarsono (1996), then these strain ratios are – in the context of this study – ratios of face cleats strain, butt cleats strain, and vertical strain due to tertiary cleats ($\varepsilon_{fc} : \varepsilon_{bc} : \varepsilon_{tc}$). These strains represent sums of strains due to closure of face cleat set, butt cleat set, and tertiary cleat set, respectively. The azimuth orientations of the cleat sets are simply in the directions normal to the calculated orientations of these strains (see again Figure 4). Using the orientation of reference line, the true orientations of the cleat sets can be determined.

Overall results of calculations using steps and Equations 2 through 7 are presented in Table 2. The calculation results obtained from Widarsono (1996) are essentially the directions of the *in situ* stresses, which coincide with the orientations of the principal strains, perpendicular to which are the orientation of the cleat sets themselves. The right column of Table 2 contains orientations of the face cleats, the cleat type of interest in this study.

In order to obtain a good presentation of the face cleat orientations, the axes of the orientations are then plotted stereographically in equal-angle or equal-area stereo-nets (Figure 7). The plot in the stereo-net characteristically exhibit scatter usually encountered in

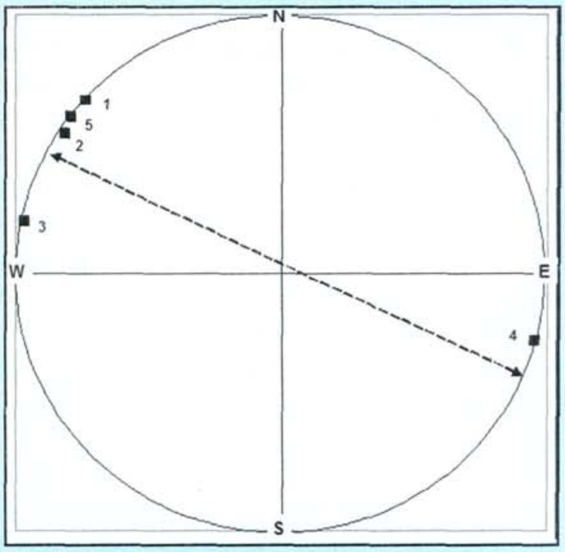

Figure 7
Stereonet projection of the orientation of face cleats. Plots are marked by their specimen number. General orientation: NW – SE, 125 °N (305 °N) (dashed line)

Table 2
Summary of DSA results. For cleat orientation, no dip is needed and therefore not presented

Specimen	Face cleat strain (ε_{fc})		Cleat orientation
	Trend (°N)	Dip (deg)	(°N)
#1	239	75	**319**
#2	220	70	**310**
#3	191	22	**280**
#4	26	52	**116**
#5	234	56	**314**

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core-based rock property evaluations. Nonetheless, based on the data from the tested five samples a general orientation of NW – SE has been concluded, with azimuth direction of 125 ^{o}N (or 305 ^{o}N). With this concluding result, it has been shown that differential strain analysis can serve well in determining cleat general orientation in coal.

V. FURTHER DISCUSSION

The face cleats general trend of NW – SE with azimuth direction of 125 ^{o}N (or 305 ^{o}N) is without doubt related to the number of specimens tested, in this case five specimens. Like in most cases of core-based rock property evaluation, sample number dictates the results. This heterogeneity-related phenomenon emphasizes that the larger sample quantity the more reliable the overall conclusion, even though classifications and grouping should also be taken into consideration. With five specimens tested a general face cleat orientation has been indicated, and more tested specimens will probably change the overall picture. Nevertheless, results from this only limited number of specimens have proved encouraging.

Results of DSA tests in the coal specimens have provided evidence that even though the strain gauges used in the tests are attached to the specimen's surface, the invisible cleats in their interior can be detected for their strains and orientations. This is indeed certainly due to the stress/strain tensor analysis. One question remains is that whether the indicated cleats are really cleats or some other form of inelastic deformations. Judging from the stress – strain curves, as ones shown in Figure 6, with their conspicuous two slopes and a long transition region it is no doubt that the indicated deformation belong to closure of relatively large cleats. As put by Close (1993), coal is too brittle a rock not to be fractured whenever subjected to dehydration and underground stresses during their maturation.

The tested samples were derived from sufficiently great depths, with consequence that the coal is compact and cleats are not clearly visible from outside. Yet the tests have proved themselves successful in indicating major cleats in the samples' interior. This proves the usefulness of DSA as a technique for the purpose. Arguably, the technique will work better on coals taken from shallower depths, i.e. with more distinctive cleats. This may prove correct, but experience dictates that coals with more visible cleats tend to be more brittle and this will provide extra difficulties in the specimen preparation (i.e. cutting, grinding, polishing, and strain gauge attachment) leading to problematic testing. Problematic testing usually means less reliable outcome. More caution has to be taken in dealing with this kind of coals.

VI. CONCLUSIONS

Investigation over the usefulness of DSA for determining face cleats orientation has yielded several main conclusions:

1. DSA technique has proved itself useful for determining face cleats orientations in the specimens tested. With support of stress/strain tensor analysis, face cleats in the specimens' interior can be indicated.
2. DSA works well on compact bituminous coal used in testing. The technique is likely to work even better on less compact coal with more distinctive cleats. Caution has to be taken, however, in relation to specimen preparation and operational aspects.
3. Scatter of the face cleat orientations observed from the stereo-net plot is undoubtedly caused by micro-scale heterogeneities that deviates the cleats' local trends from the general orientation. As this occurrence is common to techniques based on core samples, one way to solve this is by testing a sufficiently large quantity of samples.
4. The success of DSA for determining cleat orientation has added value into what information core samples can provide. Standard visual description made from outside samples is enriched by information over the rocks' interior provided by this technique.

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