

A DIGITAL IMAGE ANALYSIS METHOD FOR MONITORING CRACK GROWTH IN METAL FATIGUE TESTING

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"I have never let my schooling interfere with my education". - Mark Twain (1835 - 1910)

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Abstract

Metal fatigue tests are an everyday occurrence that updates existing fatigue libraries, ensuring that structures and components do not fail when in use. The American Society for Testing and Materials (ASTM) provides standard tests whereby certain material properties are obtained by the exact same method for each test, providing designers the information to prevent premature failure. The Fatigue Crack Growth Rate (FCGR) of a standard specimen provides information for situations where a crack may exist in components. The critical size of the crack determines when it is safe to use a component and when to discard it.

Testing methods relating to fatigue crack growth propagation rates vary with respect to requirements and conditions. A wide variety of test methods can be utilised to find reliable data. One such a method uses a travelling microscope. It has been extensively used with success, but requires constant stoppages for measurements and user attention to make interval measurements. Alternative measurement methods have solved these disadvantages but have generally been of the contact and indirect types. Contact to the specimen may in some cases influence the results negatively, while indirect methods generally require previously obtained data to calibrate the results.

The presented digital image analysis method has in principle the same functioning as that of the travelling microscope whilst eliminating constant user attention and stoppages. The process was automated and provided a cost saving alternative to similar products available on the market. The standard test method for measurement of fatigue crack growth rates as outlined by ASTM E647 (2002) was employed to provide standardised results.

The designed and assembled test facility was put to test when a FCGR test was conducted. The set-up consisted of an Instron 1603 Electromagnetic Resonance machine, a Nikon D70 and a PC with acquired and custom written software. The digital image analysis method provided crack growth measurements with a difference of less than 1% from the actual values. Furthermore, the end result provided a Paris equation for a mild steel specimen.

Uittreksel

Metaal vermoedheid toetse word daaglik gedoen om nuwe data by bestaande vermoedheid databasisse te voeg om te verseker dat strukture en komponente nie faal terwyl dit in gebruik is nie. Standaard toetsmetodes soos uiteengesit deur ASTM (American Society for Testing and Materials), verseker dat sekere materiaal-eienskappe op presies dieselfde manier verkry word en sodoende deur die ontwerper gebruik kan word om onvoorsiene faling te voorkom. Die kraakgroei tempo van standaard toetsmonsters bied inligting vir situasies waar krake in komponente voorkom. Die kritiese grootte van die kraak bepaal wanneer 'n komponent veilig gebruik kan word en wanneer die gebruik daarvan gestaak moet word.

Kraakgroei toetsmetodes varieer met betrekking tot die toetsvereistes en toestande. 'n Wye verskeidenheid toetsmetodes word gebruik om betroubare data te verkry. Die skuifmikroskoop is een van die metodes wat met welslae gebruik is, maar dit vereis dat die toets gereeld gestop moet word vir metingsdoeleindes en verder, dat die gebruiker teenwoordig moet wees vir die duur van die toets. Alternatiewe metodes het hierdie probleme opgelos, maar is oor die algemeen van die kontak metodes en indirekte metodes. Kontak metodes kan in sekere omstandighede die toets negatief beïnvloed terwyl indirekte metodes in die algemeen van beskikbare data afhanklik is om die resultate te kalibreer.

Die digitale beeldanalise metode gebruik dieselfde beginsel as dié van die skuifmikroskoop terwyl dit onderbrekings en gebruikersteenwoordigheid vermy. Die proses is geoutomatiseer en bied 'n kostebesparingsalternatief in vergelyking met soortgelyke sisteme wat kommersieel beskikbaar is. Die standaard metode vir die meting van kraakgroei tempo tydens vermoedheidstoetse soos uiteengesit in ASTM E647 (2002) is gebruik om gestandaardiseerde resultate te verkry.

Die ontwerp en samestelling van die toetsfasiliteit is getoets deur middel van 'n vermoedheidstoets waartydens kraakgroei gemonitor is. Die opstelling het bestaan uit 'n Instron 1603 elektromagnetiese resonansmasjien, 'n Nikon D70 digitale kamera en 'n rekenaar met kommersiële en selfgeskrewe sagteware. Die digitalebeeld analise metode se meetresultate het met minder as 1% van die werklike waardes verskil. Verder, het die eindresultaat 'n Paris vergelyking vir die sagte staal toetsmonster gelewer.

Nomenclature

a	-	Crack length
a_{crack}	-	Crack length measured by the program
$\bar{a}$	-	Average crack length (Secant method)
$\hat{a}$	-	Average crack length (incremental Polynomial method)
α	-	Ratio of crack length to specimen width (a/W)
b_0, b_1, b_2	-	Regression parameters used in the Polynomial method
B	-	Specimen thickness
C	-	Intercept of the linear $\log da/dN$ versus $\log \Delta K$ plot
C_1, C_2	-	Scale parameters used in the Polynomial method
l_{max}	-	Length of object's longest axis
l_{min}	-	Size of object's smallest feature
K	-	Stress intensity factor
K_{IC}	-	Fracture toughness
K_c	-	Critical stress intensity factor
K_{th}	-	Stress intensity threshold
K_{max}	-	Maximum stress intensity factor
ΔK	-	Cyclic stress intensity parameter
m	-	Slope of the linear $\log da/dN$ versus $\log \Delta K$ plot
N	-	Number of cycles
P_{min}	-	Minimum load
P_{max}	-	Maximum load
PR_{min}	-	Minimum pixel resolution
S	-	Stress
W	-	Specimen width
da/dN	-	Fatigue crack growth rate

Other

$\otimes$	-	Tip
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Abbreviations

AC	-	Alternating Current
AE	-	Acoustic Emission
ASM	-	The Materials Information Society
ASTM	-	American Society for Testing and Materials
BNC	-	Bayonet Neill-Concelman (cable type)
CCD	-	Charge Couple Device
CGM	-	Crack Growth Monitoring
CMOS	-	Complementary Metal-Oxide Semiconductor
CMOD	-	Crack Mouth Opening Displacement
CT	-	Compact Tension (Specimen)
DAQ	-	Data Acquisition
DC	-	Direct Current
ESPI	-	Electronic Speckle Interferometry
EMR	-	Electromagnetic Resonance
FCGR	-	Fatigue Crack Growth Rate
GB	-	Gigabyte
IMAQ	-	Image Acquisition
i/o	-	Input/output
LEFM	-	Linear Elastic Fracture Mechanics
MB	-	Megabyte
NDT	-	Non-destructive Testing
NI	-	National Instruments®
PC	-	Personal Computer
PCI	-	Personal Computer Interface
PD _{meas}	-	Measured Potential Drop
PD _{ref}	-	Reference Potential Drop
PBMR	-	Pebble Bed Modular Reactor
RAM	-	Random Access Memory
SAE	-	Society of Automotive Engineers
SEM	-	Scanning Electron Microscope
SLR	-	Single Lens Reflex
SN	-	Fatigue strength – cycle life
TPB	-	Three Point Bend

Other

.jpg	-	Joint Photographic Experts Group (Image file type)
.png	-	Portable Network Graphics (Image file type)
.scr	-	Script File (NI Vision Assistant file extension)
.vi	-	Virtual Instrumentation (LabVIEW file extension)

Table of Contents

CHAPTER 1 - Introduction	1
1.1 Preface	1
1.2 Background	1
1.3 References	3
CHAPTER 2 - FCGR Background	4
2.1 Introduction and Motivation	4
2.2 Crack Growth Measurements: Background to FCGR and Related Topics	4
2.3 Crack Growth Measurement Methods	9
2.3.1 Traditional Crack Growth Measuring Methods	10
2.3.2 NDT Crack Detection Methods	13
2.4 Latest Techniques in Deformation and Crack Growth Monitoring	18
2.5 Discussion	24
2.6 Conclusion	26
2.7 References	27
CHAPTER 3 - The Design and Assembly of the Testing Facility	31
3.1 Introduction	31
3.2 Task Clarification	32
3.2.1 User Specification Requirement	32
3.3 Conceptual Design	33
3.3.1 Equipment Options	33
3.3.2 Concept	36
3.4 Embodiment Design	38
3.4.1 Equipment Selection	38
3.4.2 Software Selection	39
3.4.3 Preliminary Layout	41
3.4.4 Definitive Layout	42
3.5 Embodiment Design: The Set-up Requirements	43
3.5.1 Specimen	43
3.5.2 Lighting	43
3.5.3 Camera Settings	46
3.6 Embodiment Design: The Main Program	46
3.6.1 Calibration	46
3.6.2 The LabVIEW Program (CGM.vi)	47
3.7 Embodiment Design: Post-processing Programming	59
3.8 Documentation	61
3.9 Conclusion	62
3.10 References	64

CHAPTER 4 - The Experiment	65
4.1 Introduction	65
4.2 The Specimen and Loading Considerations	65
4.3 Test Results	67
4.4 References	73
CHAPTER 5 - Processing of Results	74
5.1 Introduction	74
5.2 Post-processing	74
5.3 Discussion of Results	75
5.4 References	78
CHAPTER 6 - Conclusion and Discussion	79
6.1 Conclusion	79
6.2 Advantages and Disadvantages of the Method	80
6.3 Recommendations	80
APPENDIX A - Operating Manual	82
A.1 Introduction	82
A.2 Program Functionality	82
A.3 Equipment	82
A.4 Program Requirements	83
A.5 Program Use	84
A.6 Data Acquisition	85
A.7 Post-processing	85
A.8 References	86
APPENDIX B - Procedure for Image Calibration	87
B.1 Requirements	88
B.2 Opening	88
B.3 Subtract Constant	88
B.4 Pattern Matching Set-up	89
B.4.1 Pattern Matching 1	90
B.4.2 Pattern Matching 2	91
B.4.3 Pattern Matching 3	91
APPENDIX C - LabVIEW Programs	96
C.1 The Sub-vi (CTSpecImage.vi)	96
C.2 The Main Program (CGM.vi)	97
C.3 Post-processing (CGMPostProc.vi)	98

APPENDIX D - CT-Specimen	99
D.1 Specimen Geometry	99
D.2 Specimen Preparation	100
D.3 References	101
APPENDIX E - Connection	102
E.1 BNC-Cable Numbering	102
APPENDIX F - Additional Test Data.....	104
F.1 Mild Steel Specimen.....	104
APPENDIX G - Software (CD)	105
G.1 CD-Content.....	105

List of Figures

Figure 2-1: The CT-specimen.....	4
Figure 2-2: Basic modes of crack (surface) displacement for isotropic materials (modified after ASTM E1823-96, 2002).....	5
Figure 2-3: Constant amplitude loading (modified after ASTM E1823-96, 2002).	5
Figure 2-4: Variable amplitude loading (also called spectrum loading) (modified after ASTM E1823-96, 2002).	6
Figure 2-5: Crack growth rate and development (modified after Flinn, 1995:984).....	6
Figure 2-6: Principal types of load-displacement records (modified after ASTM E399, 2002:8).....	8
Figure 2-7: NDT-methods for surface inspection and detection of cracks (modified after Boyes, 2003:566).	9
Figure 2-8: NDT-methods for subsurface inspection and detection of cracks (modified after Smith, 2000:7/171).	10
Figure 2-9: Typical extensometer for measuring the CMOD used in the compliance method.....	10
Figure 2-10: Correlation between visually measured a/W and a/W calculated from the compliance method for TPB specimens (Sriharsha et al. 1999:620).	11
Figure 2-11: Schematic diagram of the AC potential system (modified after ASTM E647, 2002:22).	12
Figure 2-12: Effect of crack orientation on delectability using ultrasound (Pope, 1997:346).	13
Figure 2-13: In situ monitoring of fatigue surface crack initiation and propagation in Inconel 718 sample (Rokhlin, 2002:46).	14
Figure 2-14: Schematic diagram of the magnetic flux experiment surface (modified after Saka et al., 1998:326).	15
Figure 2-15: Flow principle of eddy current testing (modified after Boyes, 2003:575).	15
Figure 2-16: Test specimen and X-ray set-up (modified after Wang & Barkey, 2004:513).....	17
Figure 2-17: Principles of neutron diffraction (modified after Webster and Wimpory, 2001:396).....	17
Figure 2-18: Schematic drawing of the strain measurement system using a laser extensometer (modified after Yonekawa et al., 2002:1615).	18
Figure 2-19: Optical System: (modified after Diaz et al., 2003:479).....	19
Figure 2-20: Schematic diagram of the experimental set-up of an acoustic emission system including a CCD-camera (modified after Yoon et al., 2000).....	20
Figure 2-21: Moiré displacement data from a typical specimen (Fellows & Nowell, 2004:1078).	21
Figure 2-22: Crack opening displacement profiles during loading (Fellows & Nowell, 2004:1080).	22
Figure 2-23: Holographic set-up (Gryzagoridis, 2001).	23
Figure 2-24: Observation window of a vacuum chamber for use with video extensometer (Messphysic, 2003).	25
Figure 3-1: Schematic illustration of test components.....	31
Figure 3-2: Set-up requirements of crack growth monitoring system.....	32
Figure 3-3: The Instron 1603 Electromagnetic Resonance (EMR) machine.....	33
Figure 3-4: Relationship between field of view, focal length, sensor size and working distance.	36

Figure 3-5: Concept 1 – Layout for CGM through an optical method.....	37
Figure 3-6: Concept 2 - Layout for CGM through an optical method.	37
Figure 3-7: Nikon D70.....	39
Figure 3-8: Illustration of the equipment and software and their related topics.....	41
Figure 3-10: Required data for crack growth rate.....	42
Figure 3-11: Experimental set-up.	43
Figure 3-12: Lighting for CT-specimen.	44
Figure 3-13: Picture of the actual camera and layout of the lights.	44
Figure 3-14: Required lighting condition.	45
Figure 3-15: Order of program actions.	48
Figure 3-16: The initial tab.	49
Figure 3-17: User input check.....	50
Figure 3-18: The information tab.	51
Figure 3-19: DAQ assistant function.....	52
Figure 3-20: Inputs and outputs of the sub-vi CTSpeclImage.vi.	53
Figure 3-21: CTSpeclImage.vi front panel.....	54
Figure 3-22: Fine crack for K450.	55
Figure 3-23: Processed image for the fine crack of K450.	55
Figure 3-24: Crack length for mild steel.....	55
Figure 3-25: Processed image for the crack length of mild steel.	55
Figure 3-26: Crack length measurement.	56
Figure 3-27: Reference points on the image.	57
Figure 3-28: The procedure for running the test.....	61
Figure 3-29: Simplified sub-vi operation.	62
Figure 3-30: Simplified illustration of program operation.	63
Figure 4-1: K_{max} boundaries for crack propagation through test.....	66
Figure 4-2: Real time LabVIEW representation of the actual crack length vs. time.....	67
Figure 4-3 Crack length vs. time with indicated problem areas.....	68
Figure 4-4: Cause of a faulty measurement.	69
Figure 4-5: Actual measurements and LabVIEW measurements.	70
Figure 4-6: Percentage difference from LabVIEW data to actual data.....	71
Figure 4-7: Corrected crack growth propagation data.	72
Figure 5-1: Graph of da/dN vs. ΔK with error.	74
Figure 5-2: Fitted lines for the for da/dN vs. ΔK for the Polynomial and Secant methods.	75
Figure 5-3: Secant and Polynomial results for da/dN vs. ΔK for mild steel.....	76
 Figure A 1: Illustration of the equipment.	 83
Figure A 2: Base directory - content, allocation and essential files.	84
 Figure B 1: Subtract constant icon.....	 88

Figure B 2: Histogram operation.....	89
Figure B 3: Image with indicated pattern matching selections.	90
Figure B 4: Pattern matching 1 icon.....	90
Figure B 5: Upper corner of CMOD opening and Centre alignment with corner.	91
Figure B 6: Area selection for reference point location.....	92
Figure B 7: Crack corner pattern selection note.	93
Figure B 8: Pattern matching set-up, template tab.	93
Figure B 9: Calliper 2 - Angle measured from horizontal to the line connecting points 3 and 4.....	94
Figure B 10: Calibrated image with numbered points and axis definition.....	95
 Figure D 1: Standard Compact Tension (CT) specimen for FCGR testing (modified after ASTM E647, 2002:11).	 99
Figure D 2: Out of plane cracking limits (ASTM E647, 2002:8).	100

List of Tables

Table 2-1: Evaluated results and the crack sizes observed on the fractured surface (modified after Saka et al., 1998:327)	15
Table 3-1: The time it takes to save an image (jpeg) to file.....	40
Table 3-2: Camera settings.	46
Table 3-3: General functions and icons used in LabVIEW and IMAQ Vision Concept Manual (NI, 2003: 3-1 – 3-8)	57
Table E 1: BNC cable output and description.....	102
Table E 2: BNC-cable connection to connector block.	103
Table G 1: Description of CD-content.	105

CHAPTER 1 - Introduction

1.1 Preface

The Fatigue Crack Growth Rate (FCGR) is important in estimating the life expectancy of components that are subjected to variable loading. Fatigue crack growth data collected over a wide range of conditions, loads and frequencies enable designers to understand and predict material changes in these components. Once this is understood, accurate predictions can be made on life expectancy, whether it is related to fracture safe or crack initiation safe design.

A continuous need exists to monitor crack growth in fatigue testing as new materials, many options of load cycles, and unusual environments necessitate updating of the current fatigue data for fail-safe design.

1.2 Background

Skelton (1983:6) states that the ultimate aim of fatigue experiments is to provide data which can be used in design to enable a judgement to be made on the components' lifetime. He refers to the difficulty in testing components below certain strains, which are impossible in testing and that certain critical components may be required to operate for up to 30 years. Therefore, it is required to understand the material changes that occur. The defect tolerance approach recognises that cracks may sometimes be acceptable provided that their progress is slow, stable and well characterised by microstructure.

Crack growth monitoring (CGM) forms part of the Linear Elastic Fracture Mechanics (LEFM) approach to fatigue. "Due to the fact that most structures have inherent flaws, or develop cracks relatively early in life, considerable interest has developed in the crack propagation stage of fatigue" (Colangelo, 1987:10). In this stage, the crack grows from a barely discernable to a critical size. From this acquired data, a *prediction of fatigue life* can be developed.

The basic FCGR-test consists of a test machine capable of applying a variable or constant amplitude load to a standard test specimen, with an applicable notch from where crack growths initiate. Standards such as ASTM E647 (2002) specify the geometry of the specimen, as well as the procedure of the test.

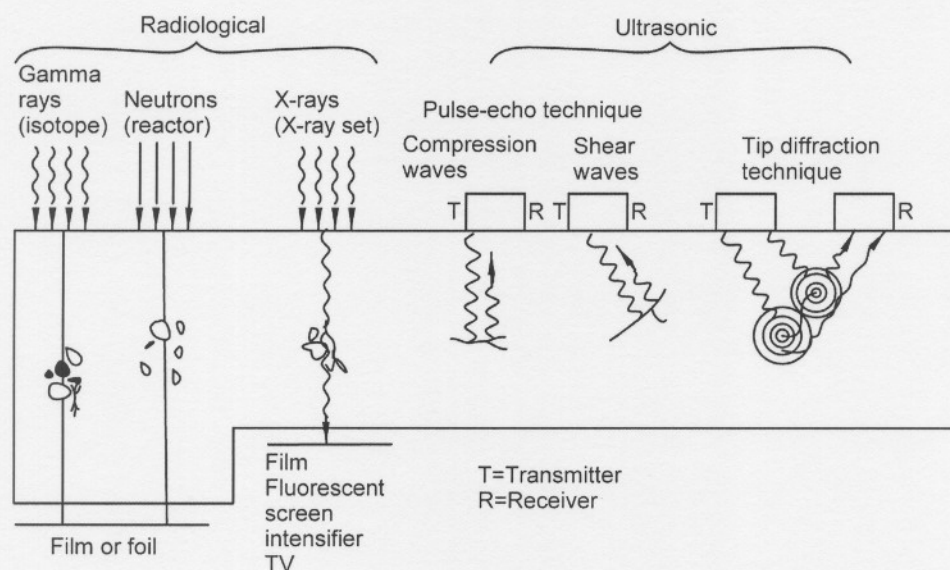


Figure 2-8: NDT-methods for subsurface inspection and detection of cracks (modified after Smith, 2000:7/171).

2.3.1 Traditional Crack Growth Measuring Methods

The following three methods are commonly used to measure the crack growth rate: the *compliance*, the *travelling microscope*, and the *potential drop technique*.

The compliance method uses a displacement gauge as illustrated in Figure 2-9, which is fixed to the face of the specimen (Riddick, 2003:53). It measures the Crack Mouth Opening Displacement (CMOD) which in turn is used to find the ratio of load to CMOD amplitudes. This ratio is used to calculate the compliance of the specimen on the unloaded portion of the cycle. The compliance is related to the crack length by a fifth order polynomial, and coefficients are chosen, based on geometrical and material properties such as Young's modulus and Poisson's ratio.

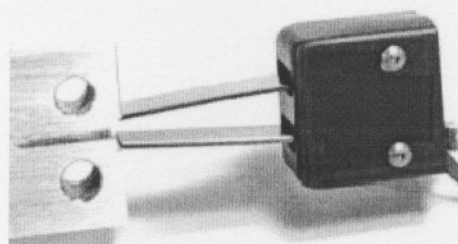


Figure 2-9: Typical extensometer for measuring the CMOD used in the compliance method.

The methods currently used to monitor crack propagation are mainly dependent on testing conditions such as temperature and atmosphere. The more traditional methods used to monitor crack growth include *optical*, *compliance* and *potential drop* methods. New and more specialised methods exist, all of which have their own limitations and advantages.

Long-term reliability is one of the main concerns in the nuclear reactor environment. The Pebble Bed Modular Reactor (PBMR) is a new nuclear development in its design phase, which will operate at high temperatures and in a helium environment. The different materials suggested for use in many of the components of the PBMR, are required to exhibit long-term reliability and to maintain integrity. The turbine blades are, among others, important components that will be subjected to these harsh environmental conditions, and are required to provide optimal performance for long periods of time. One of the main challenges in the turbine blade design is to ensure that the material does not crack, as this may have catastrophic consequences. Furthermore, in the case that a small crack does exist in the turbine blade material, it is of utmost importance that this crack does not propagate any further. The materials that are proposed for this purpose are therefore required to undergo vigorous long-term testing which include a wide variety of fatigue and creep tests in simulated conditions.

The purpose of study, therefore, was to review existing modern methods of crack growth monitoring with a view on obtaining and implementing the most appropriate currently used method and to apply this method to acquire, as yet, unpublished fatigue crack growth data of current materials.

1.3 References

ASTM E647-00. 2002. *Standard Test Method for Measurement of Fatigue Crack Growth Rates*. 42 p.

COLANGELO V.J. & HEISER F.A. 1987. *Analysis of metallurgical failures*. 2nd ed. New York: Wiley. 360 p.

SKELTON, R.P. 1983. *Fatigue at High Temperature*. London: Applied Science Publishers. 409 p.

CHAPTER 2 - FCGR Background

2.1 Introduction and Motivation

The following sections will provide more insight into the implementation of fatigue theory to solve the issue of material failure and into the identification of the standard and variable experimental parameters. More specifically it will clarify how and when the tried and tested methods and standards are used and assist in the identification of available new methods and the ways in which they can be implemented or altered.

The first topic of discussion is the theory surrounding the methods of crack growth monitoring.

2.2 Crack Growth Measurements: Background to FCGR and Related Topics

One may ask the following question: Why all the fuss about the crack growth and where can it be used? In order to answer the question, applicable theory to crack growth measurement is discussed in the following section.

Material testing related to fatigue uses various kinds and sizes of specimens to find different characteristics. In general, deformation measurements are recorded while a load is applied to the specimen. There are a number of types of specimen geometries associated with standard fatigue tests. The main difference between these types is their application and for this dissertation the focus falls on the notched type. To be more specific, a Compact Tension (CT) specimen is used, as illustrated in Figure 2-1:

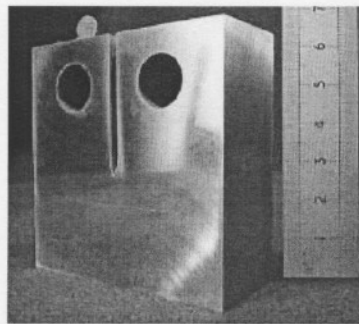


Figure 2-1: The CT-specimen.

The loading of the specimen can occur in one of the following modes:

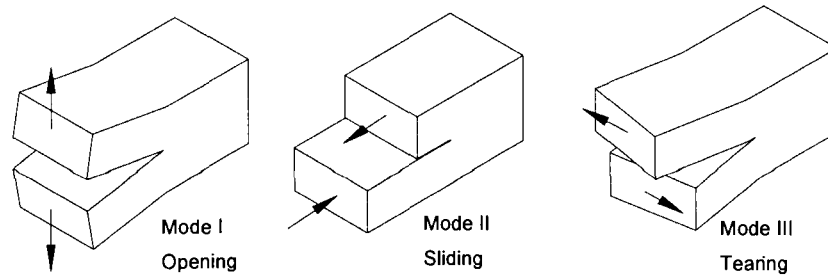


Figure 2-2: Basic modes of crack (surface) displacement for isotropic materials (modified after ASTM E1823-96, 2002).

The basic modes of crack displacement according to Pook (1983:46) are:

- The opening mode (mode I);
- The edge sliding mode (mode II). The crack surfaces move normal to the crack front and remain in the crack plane; and
- The shear mode (mode III). The crack surfaces move parallel to the crack front and remain in the crack planes.

The most commonly used mode is the opening mode (I) where the load is applied so that the crack surfaces move directly apart. The load can be applied by either constant or variable amplitude loading. In the constant amplitude cyclic loading (Figure 2-3), the load range $\Delta P = P_{\max} - P_{\min}$ is constant throughout the entire loading history. The load varies between a minimum and a maximum, while the load amplitude remains constant.

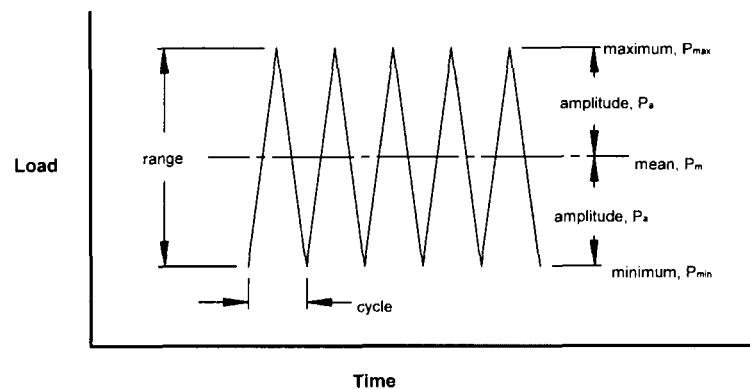


Figure 2-3: Constant amplitude loading (modified after ASTM E1823-96, 2002).

Variable amplitude loading (Figure 2-4) is often applied when component load history is available. It has the advantage that, in the case of turbines, start-up and in-service conditions can be applied, which can then directly be related to actual operation. The following figure

(Figure 2-4) shows the typical variable loading that can take place. Take note that average, peak and reversals, in the loading, play a vital role in estimates.

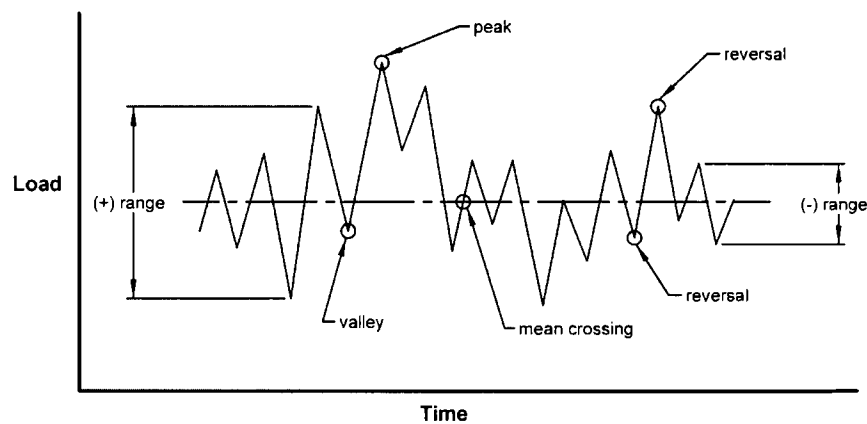


Figure 2-4: Variable amplitude loading (also called spectrum loading) (modified after ASTM E1823-96, 2002).

In simple terms, the load applied to the specimen causes deformation during which crack growth initiates and propagates. The crack growth rate is then monitored.

Pook (1983:45) states that a common range of crack growth rates for practical interest lies between 10^{-8} to 10^{-2} mm/cycle. Fracture mechanics largely deals with the macroscopic aspects of crack behaviour at scales of 10^{-1} mm/cycle. The following assumptions are made:

- The material is a homogeneous isotropic continuum;
- Stress is proportional to strain; and
- Strains are small and distortions are neglected.

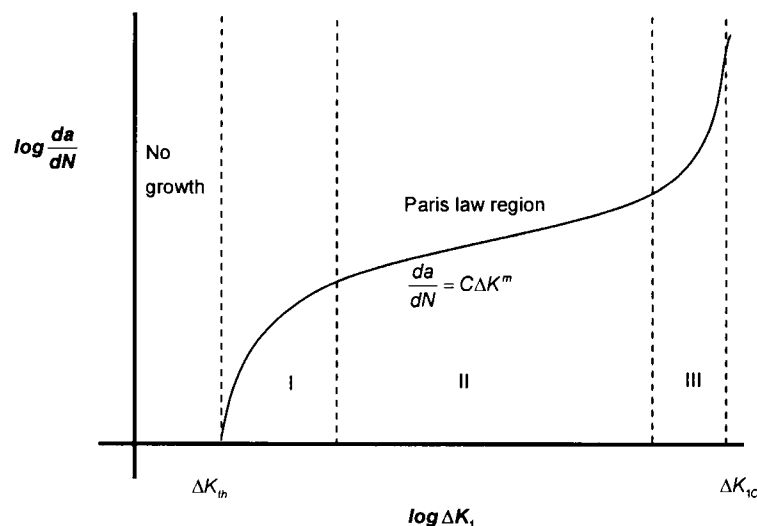


Figure 2-5: Crack growth rate and development (modified after Flinn, 1995:984).

The FCGR as illustrated in Figure 2-5, shows the three regions whereby crack growth is characterised. The vertical log scale indicates the change in crack length (a) over number of cycles (N). The horizontal scale indicates the change in the stress intensity factor. The fatigue crack growth threshold (ΔK_{th}) indicates the value of the stress intensity (ΔK) below which cracks do not grow.

Each region in Figure 2-5 can be described by means of the following:

- I) It starts with crack initiation followed by crack growth;
- II) Which is termed the power law (or Paris law) region; and
- III) Rapid, unstable crack growth occurs (ASM, 1996:168).

The stress intensity is reliant on the geometry of the specific sample. According to ASTM E647 (2002:12) the range of the stress intensity factor is calculated from the following equation for the Compact Tension (CT) specimen:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2 + \alpha)^{\frac{3}{2}}}{(1 - \alpha)^{\frac{3}{2}}} (0.866 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \quad (2.1)$$

Where P = load, B = specimen thickness, W = specimen width, a = crack length and $\alpha = a/W$. Equation (2.1) is only valid for $a/W \geq 0.2$.

It is often possible to use crack growth laws like the Paris or Foreman equation for the *prediction of life expectancy*:

The Paris Equation
$$\frac{da}{dN} = C(\Delta K)^m \quad (2.2)$$

and the Foreman Equation
$$\frac{da}{dN} = \frac{C(\Delta K)^m}{(1 - R)K_C - \Delta K} \quad (2.3)$$

where C and m are material constants which can be obtained, respectively, from the intercept and slope of the linear $\log da/dN$ versus $\log \Delta K$ plot (ASM, 1996:169). The K_C parameter in the Foreman equation indicates the critical stress intensity factor. The load ratio, R , is defined by:

$$R = \frac{P_{min}}{P_{max}} \quad (2.4).$$

The theory discussed up to now deals with fatigue crack growth rate. The practical aspect regarding the topic involves direct measurement of certain parameters. In order to construct a crack growth rate graph (as in Figure 2-5) the crack length, the load, and the number of cycles completed have to be measured simultaneously. Other FCGR related topics such as fracture

toughness and creep also use the measured crack length to find their relevant material property.

Some may say that the most important material property in terms of design, is the fracture toughness value. This value is obtained through test methods such as ASTM E1820 (2002) and ASTM E399 (2002). Once again this discussion focuses on the CT-specimen and mode (I) loading. The term K_{IC} is a material property called the fracture toughness or the material's resistance to fracture. ASTM E399 (2002) describes the standard test method for plane strain fracture toughness (K_{IC}) of metallic materials where these specimens have a thickness of 1.6 mm or greater. Furthermore, the K_{IC} value of a given material is a function of testing speed and temperature.

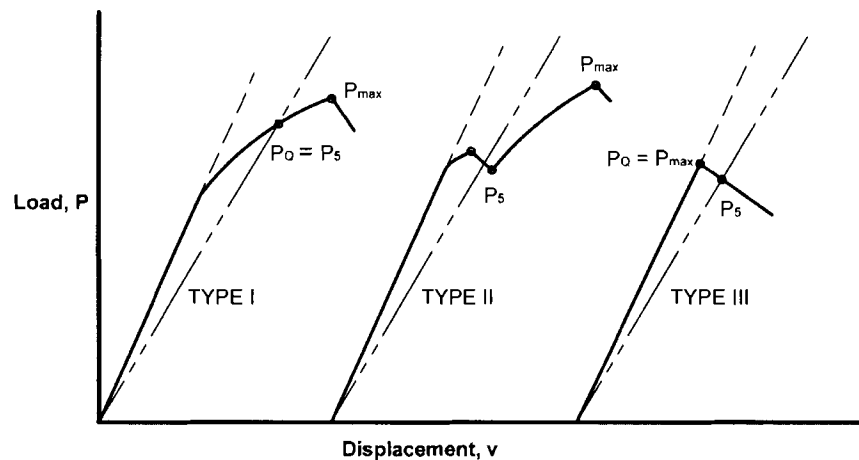


Figure 2-6: Principal types of load-displacement records (modified after ASTM E399, 2002:8).

Notched specimens, with a fatigue crack of a known size, are subjected to an increasing tensile load until fracture occurs (as indicated in Figure 2-6). Figure 2-6 also indicates the three types of load-displacement behaviour. They are: Type I, tearing (plane stress fracture); Type II, mixed; and Type III, cleavage (plane strain fracture). The indicated P_Q value and measurements of the crack length (a) after fracture is used to determine a K_Q value which $K_Q = K_{IC}$ can be deduced from if certain criteria are met. In short, the fracture toughness value is calculated by using the stress at fracture and the fracture crack size values (SAE, 1988:252).

Crack growth rates are also important in the creep regime. A typical creep crack growth rate equation is represented by Branco, *et al.* (1997:29) as

$$\frac{da}{dt} = 21.3(C^*)^{0.99} \quad (2.5).$$

Here the familiar crack length is represented by a , the creep crack growth parameter is indicated by C^* , and the time by t . The crack growth behaviour of IN718 at temperatures of 600°C and 700°C was investigated by Branco *et al.* (1997:30). CT-specimens amongst others, were monitored by means of a DC *potential drop method* to find the crack length.

Many components subjected to vibration or cyclic loads much lower than what the component can endure under static conditions, fail due to inadequate fatigue life design. It is therefore imperative to simulate test conditions as close as possible to the actual conditions. This may sometimes require that the specimen be subjected to increased temperature and complex environmental conditions. These conditions must be taken into account when selecting an appropriate measurement method.

2.3 Crack Growth Measurement Methods

A wide variety of test equipment is available on the market that is suitable for crack growth measurement methods. The different methods can be divided into two topics, namely: crack initiation or defect assessment methods, and crack propagation monitoring methods. In addition, the discussion in section 2.3.2 below, includes a few methods that are more suitable for crack detection purposes, but they are included as possible enhancement to the crack growth measurement methods. Although many of these methods may be used in both crack initiation and crack propagation methods, the focus falls on crack propagation measurement methods.

The following methods can be divided into contact and non-contact measurement techniques. The optical methods, for example, form part of the non-contact test methods and the displacement gauge compliance and potential drop methods form part of the contact test methods. Figure 2-7 illustrates some of the Non-destructive Testing (NDT) methods used in surface inspection while Figure 2-8 illustrates the NDT-methods used for subsurface inspection:

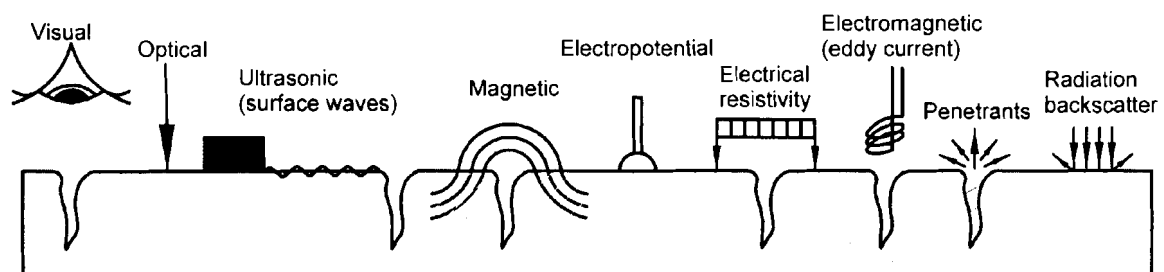


Figure 2-7: NDT-methods for surface inspection and detection of cracks (modified after Boyes, 2003:566).

To be more specific, the compliance value is expressed by the following equation:

$$C = \frac{v}{P} \quad (2.6)$$

where C represents the compliance, v the displacement between the measurement points, and P the force. The dimensionless compliance, commonly referred to as ECB, is a function of the crack length and the specimen width, and is unique for a given specimen geometry. Therefore:

$$ECB = f\left(\frac{a}{W}\right) \quad (2.7)$$

where E represents the elastic modulus, C the compliance, B the thickness of the specimen, a the crack length, and W the width of the specimen (ASTM 647, 2002:20). Note that this method requires separate calibration for each specimen or crack geometry.

Measuring crack growth by large leading companies such as the Instron® Corporation and MTS® Systems Corporation has been achieved by programs such as Fast Track 2™ (Instron, 1998) and CCM™ (MTS, 2004) respectively. These programs generally use the compliance method to find the crack growth measurement. The monitoring of the CMOD is done by a variety of compatible methods, be it a conventional clip-on gauge or a more recent video extensometer.

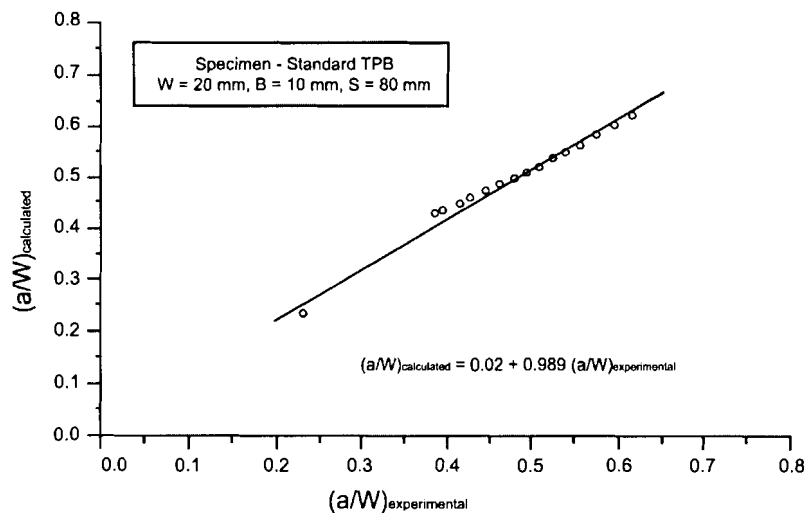


Figure 2-10: Correlation between visually measured a/W and a/W calculated from the compliance method for TPB specimens (Sriharsha *et al.* 1999:620).

Sriharsha *et al.* (1999:607) studied the constant load amplitude FCGR behaviour of A533B steel using Compact Tension (CT) and Three-point Bend (TPB) specimens. The experimental set-up used extension arms connected to the crack mouth opening of the TPB specimen. The

other end connected to a CMOD gauge. In order to investigate the validity of the experimental set-up, a travelling microscope was used to measure the crack growth. Amongst other results a comparison was made between the compliance method values and the travelling microscope measurements (see Figure 2-10). The difference in the methods was in the order of -0.04 (a/W). It could then be concluded that the extension arms had not affected the measurement in any significant manner.

The electric potential drop method measures the change in the potential drop of a current that passes through a specimen during a typical test set-up. The electrical resistance of the specimen rises as the crack increases, which in turn causes the potential drop to increase (Riddick, 2003:55). Figure 2-11 illustrates the method for an Alternating Current (AC) system which is similar to that of the Direct Current (DC) system. This method requires a calibration curve as reference for the particular test piece geometry according to ASM (1996:177) in order to measure the crack length.

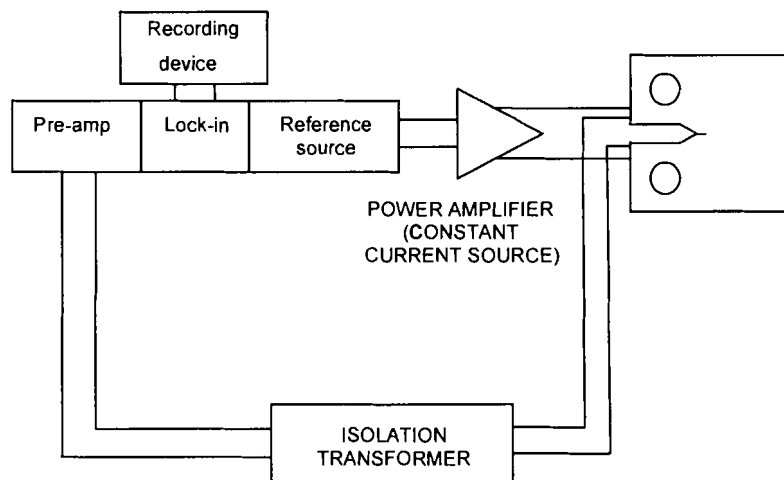


Figure 2-11: Schematic diagram of the AC potential system (modified after ASTM E647, 2002:22).

Nilsson *et al.* (2003:1727) used the DC potential drop technique to monitor the instantaneous size of the crack at 400°C. A constant current of 10 A was applied through the specimens. Thin wires of a Ni-base alloy with a diameter of 0.05 mm were spot-welded to each side of the starter crack to measure the drop in potential over the crack, PD_{meas} . Another set of wires was spot-welded in a location of the gauge section where the stress field was not influenced by the crack. These wires were used to measure a reference potential drop signal, PD_{ref} . The ratio PD_{meas}/PD_{ref} was calculated in order to eliminate any influence of temperature on the potential drop signal. This technique allowed the crack to be measured at very short cycle intervals.

2.3.2 NDT Crack Detection Methods

Optical methods commonly use the aforementioned travelling microscope at a magnification of between 20 to 50 times (ASM, 1996:174). This method requires the operator to measure crack growth at selected intervals when the test machine is stopped and is often used to verify the initial and final measurement when other methods such as potential drop methods are used. As with all optical related methods, smooth surface finish plays an important role in ensuring accurate readings.

Photography methods generally refer to taking a picture of the crack periodically. Micro-photography also forms part of this method and uses a camera mounted on a microscope to detect the crack initiation. These methods generally require the test to be stopped in order to acquire clear images.

Ultrasonic methods allow for deep penetration that detects internal cracks, by using an ultrasonic probe, held on the surface of the specimen, which transmits elastic waves into the specimen. It makes use of two stages namely: firstly, crack detection and secondly, signal estimation. Generally a piezoelectric probe receives transmitted ultrasound from the specimen. From there, the pulses are converted to electric signals and then displayed on an oscilloscope as a function of time of flight (ASM 1996:216). The wavelength of the ultrasound (typically between 0.3 and 3 mm) roughly defines the minimum size of the defect (Smith, 2000:7/176). The signal is reflected at both surfaces of the component and it can be clearly distinguished by the great deal of energy released. Similarly, a crack is detected when the signal is reflected; however the crack orientation plays an important role.

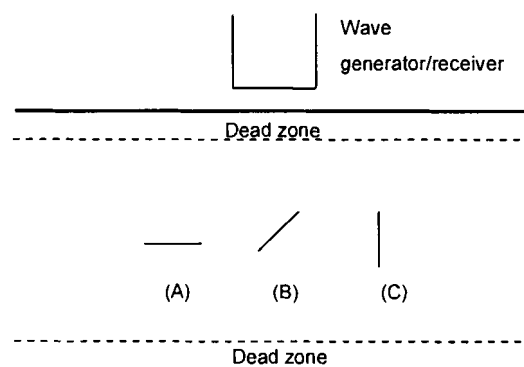


Figure 2-12: Effect of crack orientation on detectability using ultrasound (Pope, 1997:346).

Figure 2-12 illustrates three types of crack orientations. Crack orientation A is easily detected as the signal is deflected and causes a peak on the oscilloscope graph. Crack orientation B reflects a portion of the signal while the rest is deflected, and crack orientation C is difficult to

detect. The ultrasonic method is very accurate but requires a flat surface through which to apply the ultrasonic energy. This method requires referenced standards which mean an once-over test is not possible (Pope, 1997:346).

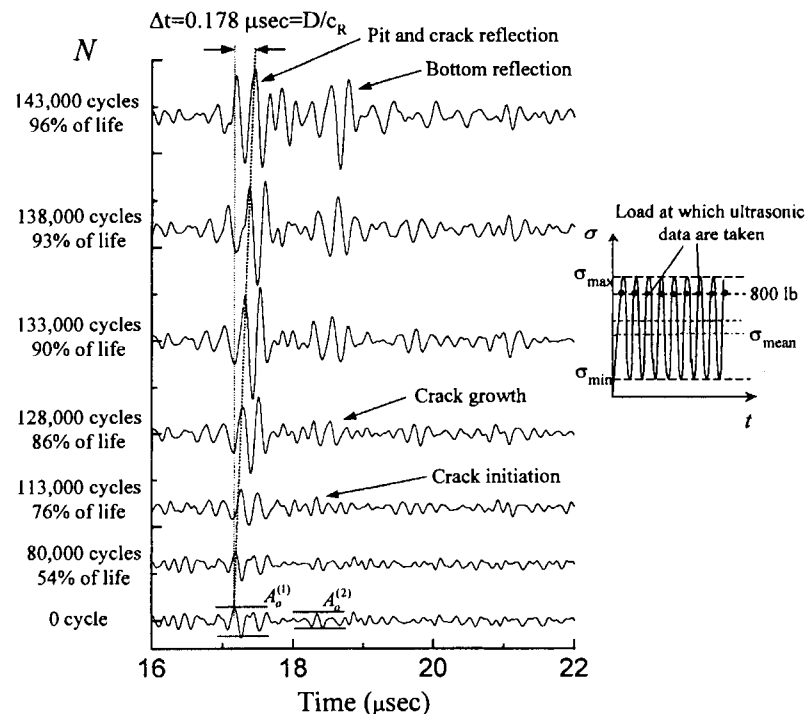


Figure 2-13: In situ monitoring of fatigue surface crack initiation and propagation in Inconel 718 sample (Rokhlin, 2002:46).

Rokhlin and Kim (2002:47) investigated surface fatigue initiation and growth through ultrasonic methods. Crack initiation and growth are quantitatively described through the interpretation of the ultrasonic reflection signals. Figure 2-13 illustrates the pit and crack reflection as well as the reflection from the bottom. It was observed that the first measurement sizes from the Scanning Electron Microscope (SEM) of the corner cracks were initially not equal to that of the ultrasonic method, but eventually their sizes came close together with growth.

A non-destructive method was proposed by Saka *et al.* (1998:326) to evaluate a three-dimensional surface crack by means of a magnetic field. The fatigue cracked specimen was machined to only show the crack, after which the NDT-method was applied. The specimens were broken to measure the actual sizes in order to be compared. A DC current of 1 A was applied to the specimen through input and output probes. The magnetic flux density was measured by a Gauss meter and the y-position of the centre of the sensor, which was 10 mm

long in the z-direction, that is the lift-off distance, was 4 mm above the centre of the crack length.

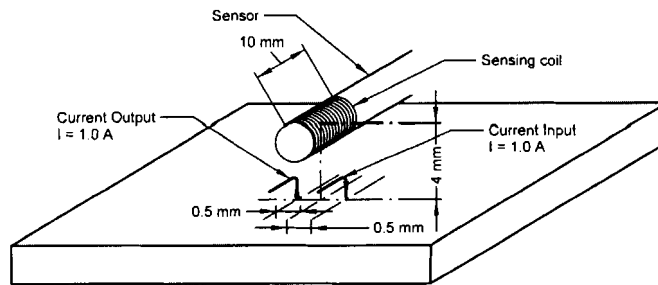


Figure 2-14: Schematic diagram of the magnetic flux experiment surface (modified after Saka et al., 1998:326).

The measurement results are listed in Table 2-1. It is clear from the results that the method was verified. The authors further noted that the method was valid if the cracks were not extremely small in comparison with the distance between the current input and output probes.

Specimen no.	Actual crack length (mm)	Actual crack depth (mm)	Evaluated crack depth (mm)
1	10.2	1.3	1.13
2	11.0	2.1	2.07
3	17.6	4.2	4.12

Table 2-1: Evaluated results and the crack sizes observed on the fractured surface (modified after Saka et al., 1998:327).

The usual eddy current testing system comprises a coil which, due to the applied current, produces an AC magnetic field within the material. This, in turn, excites the eddy currents which produce their own field, thus altering that of the current. It also reflects in the impedance of the coil, whose resistive component is related to eddy current losses and whose inductance depends on the magnetic circuit conditions. The higher the frequency, the less the depth of penetration (Boyes, 2003:570).

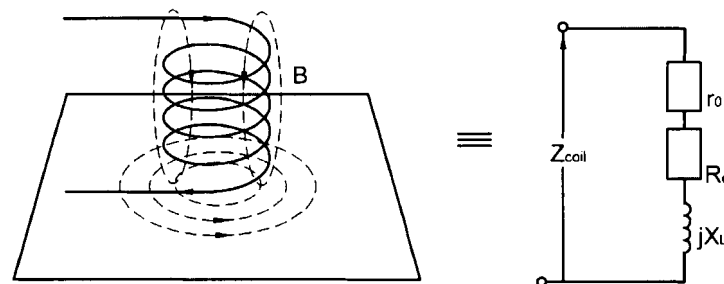


Figure 2-15: Flow principle of eddy current testing (modified after Boyes, 2003:575).

A time-changing magnetic field is used to induce weak electrical currents in the test material, these currents being sensitive to changes in both material conductivity and permeability. The intrinsic value of the conductivity depends mainly on the material composition, but is influenced by changes in structure due to crystal imperfections (voids or interstitial atoms), stress conditions, or work hardening, dependent upon the state of dislocations in the material. Additionally, the presence of discontinuities was found to disturb the eddy current flow patterns giving detectable changes.

Penetrant methods are mainly used to identify cracks that exist in components. According to SAE (1998:148) the method uses a developer and a blotter to identify the crack. First, the surface is cleaned and a liquid containing the dye is applied. After removing the excess penetrant and waiting for a while, a developer is applied. The penetrant which was drawn into the cracks through capillary action, is drawn out of the cracks by the blotter action of the developer. The colours of the developer and the penetrant are of high contrast and fluorescent types are also available. In general, the application is limited to flaw detection.

Boyes (2003:561) refers to radiation backscatter as used by the beta-backscatter gauge. It is used to measure the thickness of coatings when the surface is only accessible from the one side, and when the backing material is made from a different material that has a significantly different atomic number. An enclosure holds the radioisotope source and detector. When an uncoated item returns a measurable value, the same coated item returns a different value. The difference between these two values then results in the thickness measurement. This method may be useful when a coating is applied to a fatigue specimen to assist contrast requirements or to prevent oxidation in hazardous environments.

Diffraction methods refer to X-ray and neutron diffraction methods. Fatigue cracks have been examined with high resolution X-ray equipment. This method enables internal cracks to be monitored, but requires the test to be frequently stopped to examine the specimen. The X-ray diffraction method is non-destructive as only the X-ray and no other part touches the specimen. Wang and Barkey (2004:512) used X-ray imaging to determine the crack growth behaviour of spot-welded specimens. The method made use of previously acquired fatigue strength – cycle life (SN) data to predict the behaviour of the specimen. Previously, cracks have initiated near the nugget and between the two welded sheets (Figure 2-16). This made the process of measuring the crack very difficult. The method proved to be very effective. A scratch applied to the surface between two sheets was clearly picked up and measured 0.05 mm in depth and 0.1 mm in width. These measurements were made directly from the images obtained by the X-ray passing through the sheets to the film.

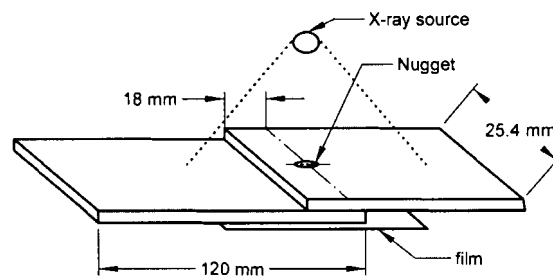


Figure 2-16: Test specimen and X-ray set-up (modified after Wang & Barkey, 2004:513).

Neutron diffraction is the only method that allows non-destructive stress measurement within a component (Webster and Wimpory, 2001:395). Even though this method is not directly related to crack measurement it is worth mentioning as part of the loading estimation and NDT-methods. Residual stresses created during manufacturing can have a detrimental effect on the load capacity and resistance to fracture of these components. The method used by Webster and Wimpory (2001:396) aimed to quantify these stresses. The incident beam of neutrons on a crystalline material created a diffraction pattern with sharp maxima. The angular position was then computed for a family of crystallographic planes of separation. The lattice strain in the direction of the scattering vector, Q , was determined by the change in lattice spacing, Δd , which corresponded to a shift in the angular position of the reflection (Figure 2-17). To calculate the strain, the unstressed lattice spacing d_0 had to be known. Furthermore, measurements in six orientations were required to completely define the strain tensor at a point. Strain was then measured by the individual peaks of the entire spectrum. The method provided strains at a resolution of 10^{-4} , which corresponded to a stress of $\pm 7\text{-}20$ MPa.

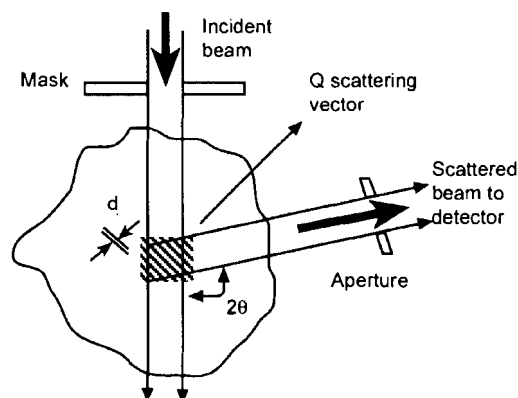


Figure 2-17: Principles of neutron diffraction (modified after Webster and Wimpory, 2001:396).

2.4 Latest Techniques in Deformation and Crack Growth Monitoring

Bryan and Ahuja (1993:1086) made a few suggestions relating to further research on crack growth. They advocated further developments on the non-metallic methods, environmental effects, alternative geometries that have received little attention, and the utilisation of (recent) advances in image processing techniques. This following section investigates the latest technologies in deformation and crack growth in order to find possible alternatives to the more common techniques.

There are a number of ways to determine the measurable parameters such as the crack length (a) and the deformation of the specimen (CMOD). In the case of the CT-specimen, an extensometer or a clip-on displacement gauge is used to measure the displacement of the opposing faces of the machined notch in the specimen. Could the displacement gauge, for instance, then be replaced by another device?

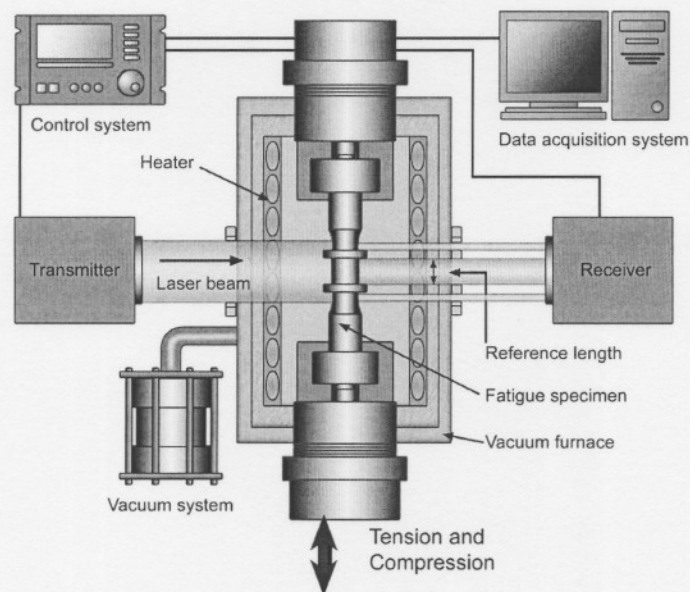


Figure 2-18: Schematic drawing of the strain measurement system using a laser extensometer (modified after Yonekawa *et al.*, 2002:1615).

Yonekawa *et al.* (2002:1614) designed an experimental set-up that incorporates the environmental conditions (Figure 2-18). A remote-controlled high temperature fatigue test machine, consisting of a vacuum furnace, vacuum system and a heater to simulate the required conditions was developed. It also made use of a nickel-chromium alloy heater in the furnace. The equipment included thermocouples installed in the upper test rod and a laser extensometer to measure the deformation. Figure 2-18 indicates the laser transmitter and receiver, as well as

the reference length which was required to correlate the measurements made. The scanning range for the laser extensometer was 0.5 to 55 mm with an accuracy of $\pm 3 \mu\text{m}$.

Dogan and Horstmann (2003:427) studied the deformation and crack growth under high temperature creep and creep/fatigue conditions. This type of study required reliable, long-term continuous measurements for accurate data acquisition. A non-contact remote displacement measurement technique was chosen. To be more specific, a laser scanner was employed to measure displacement on a flat tensile specimen surface, and on side surfaces of fracture mechanics specimens. The method had the advantage of being non-contact and therefore avoiding the problem of grooves or indentations oxidation. Furthermore, it avoided the medium refractory problems of optical and interferometric non-contact techniques.

Advances in the past few years have made the digital revolution a promising alternative to conventional methods of strain monitoring. Vial (2004:33) investigated CCD-camera systems firstly using one, then two and finally three cameras at a time. Each of these systems monitored markings made on the surface of the tensile specimen. Elongation of the specimen was measured through the difference in displacement between the markings. Contrast between the markings and the specimen colour provided accurate measurements. Vial (2004:34) also noted that *higher resolution* is required in metals testing.

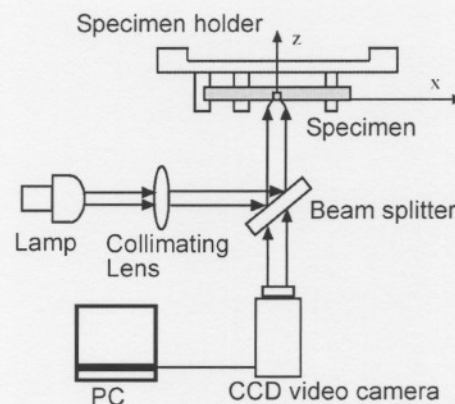


Figure 2-19: Optical System: (modified after Diaz *et al.*, 2003:479).

A non-destructive evaluation of fatigue damage accumulation around a notch was carried out at the National University of Rosario in Argentina (Diaz *et al.*, 2003:477). They made use of a contrast correlation method to evaluate plastic damage from two images acquired before and after the introduction of fatigue deformation. It was found that a non-contact digital image measurement system was very useful to study fatigue damage accumulation. This method allowed the authors to conclude that the crack growth rate for the specific sample and

conditions was abnormal. They were also able to describe the crack growth direction, the plastic damage, and to explain a softening effect. The experimental set-up (Figure 2-19) used a white light which was collimated (put in line) by a lens and then deviated by a beam splitter to illuminate the specimen perpendicularly. The PC included a digital image processing system. Diaz *et al.* (2003:479) acquired the image through a CCD-camera with a resolution of 512 x 512 pixels x 8 bits (256 grey levels). The optical magnification obtained a physical size of 149 pixels/mm in both the horizontal and vertical directions.

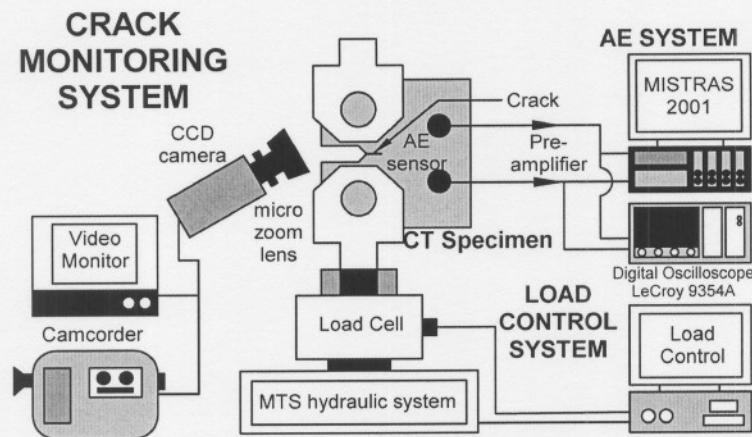


Figure 2-20: Schematic diagram of the experimental set-up of an acoustic emission system including a CCD-camera (modified after Yoon *et al.*, 2000).

Yoon *et al.* (2000) conducted fatigue cycle loading tests on a closed loop hydraulic loading machine. All of the test specimens were subjected to constant amplitude cyclic loading for three types of cyclic frequency of 1, 2, and 4 Hz. Noise from the hydraulic system was reduced by 10 dB through sound isolation tape. Optical crack length measurements were made using a micro zoom lens to observe the polished surface of the specimens, which had been scribed with grid lines spaced 1 mm apart. This image was recorded on a camcorder through the CCD-camera (Figure 2-20). Crack lengths were estimated to within 0.1 mm. The measurement of Acoustic Emission (AE) signals was conducted using multichannel commercial equipment. Two sensors were used in all cases, one with a resonant frequency at 300 kHz (R30) and the other with a broad band frequency at maximum sensitivity of -60 dB at 550 kHz. A preamplifier gain of 60 and a fixed threshold of 32-48 dB range were used. The preamplifier output was also fed into a four channel digital oscilloscope. Each waveform was digitised into 2 500 samples at a sampling rate of 2.5 MHz. After acquisition and storage of AE waveforms, post-analysis of waveforms and frequency spectrums were carried out. AE has been proposed as a passive warning system for detecting fatigue cracking in the prevention of sudden failures of bridge members and structures.

Völkl *et al.* (2001:21) investigated creep of platinum alloys and used an external video extensometer to measure the strain. It had the advantage of exposing no special materials to extremely high temperatures (3 300 K). The flat specimen was manufactured with four small shoulders which allowed image analysis to monitor the displacement between these points. The simplicity of the equipment offered the advantage of low costs and the added software gave the advantage of real time results.

According to Bryan and Ahuja (1993:1082) optical correlation methods, in general, use lasers and holographs to detect failures in materials. They employ scattered light from a target to recognise patterns. Sciammarella (2003:1) reviewed the latest optical techniques that measure displacement. The author lists the chronological order of the different techniques: Moiré was the first development followed by holography, speckle photography, speckle interferometry and numerical correlation of speckles.

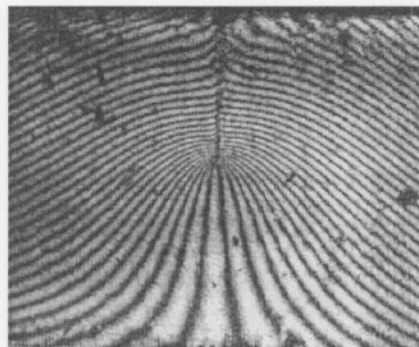


Figure 2-21: *Moiré displacement data from a typical specimen (Fellows & Nowell, 2004:1078).*

Fellows & Nowell (2004:1076) used Moiré interferometry to acquire experimental data on crack closure loads. Previous difficulties in the crack closure data, relates to the compliance and potential drop techniques giving integrated measurements across the whole of the crack. Furthermore, it can be difficult to decide on the precise moment of crack tip opening. Moiré interferometry has the advantages of submicron accuracy and providing full-field displacement maps. The main disadvantage apart from being a very sensitive optical technique is that the Moiré interferometer is normally situated in a laboratory inaccessible to the fatigue test rig. This requires the specimen to be removed from the fatigue machine and taken to another loading rig on the Moiré interferometer. This is not only time consuming but the risk of additional unwanted loads may creep into the test. For the set-up by Fellows & Nowell (2004), the Moiré interferometer was mounted directly onto the fatigue machine. The method requires that some type of grating should be applied to the surface under inspection. For this specific set-up

photoresist gratings were applied to the surface of the specimen. This type of grating eliminated previous problems experienced with pre-manufactured aluminium gratings that became delaminated after a few fatigue cycles.

Figure 2-21 indicates that the Moiré fringe pattern is more tightly packed around the crack tip. This may cause noisy data but a small field of view (2.0×2.0 mm) and a semi-automated method worked very well to eliminate this problem. The top of the specimen was taken as the reference point. The change in displacement of the pixel from the reference position was logged in a 256×256 pixel array for each load step. Each pixel corresponded to an area of 8×8 μm .

Figure 2-22 below shows the crack opening displacement with referenced distance from the crack tip obtained with this method. Furthermore, Fellows and Nowell (2004:1082) used this data to correlate it with the modelled data. They found that their simple strip-yield model of plasticity-induced-closure provided promising results.

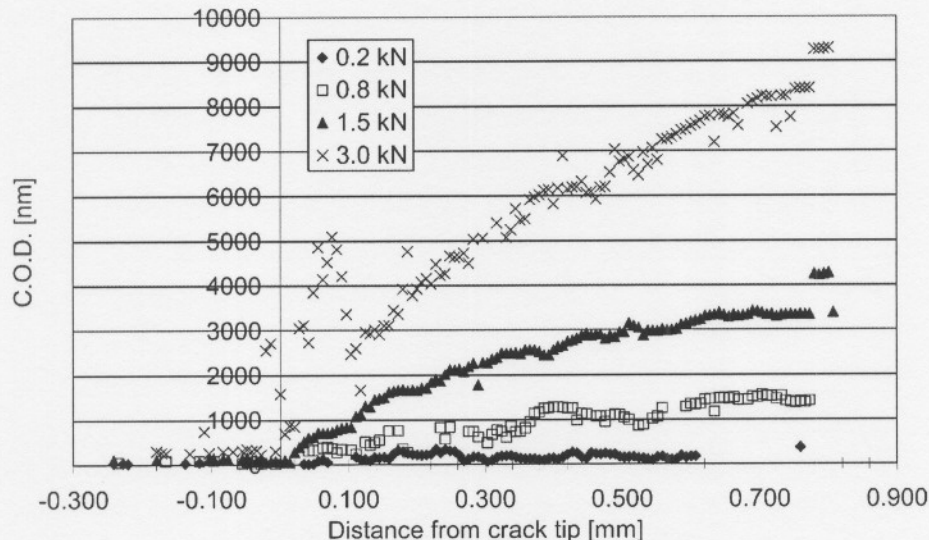


Figure 2-22: Crack opening displacement profiles during loading (Fellows & Nowell, 2004:1080).

Holographic interferometry uses the ability to record two slightly different scenes and display the small difference between them. The set-up of such a method is schematically shown by Gryzagoridis (2001) in Figure 2-23. A laser is used to superimpose the image of an object (real time) onto another image of the object stored on an emulsion type film. The interference creates contour lines that are a measure of the amount of dimensional change of the object's two stress ranges. This method allows for straightforward surface and micro crack detection.

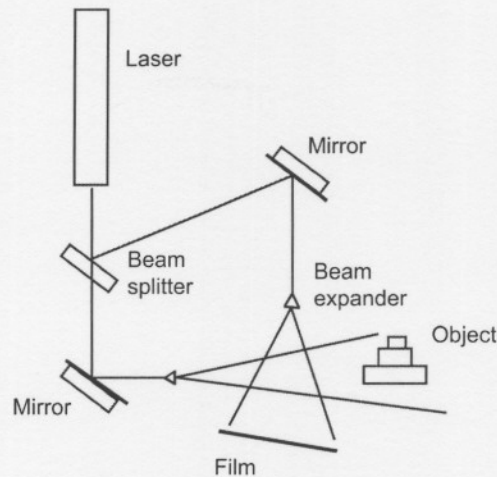


Figure 2-23: Holographic set-up (Gryzagoridis, 2001).

Electronic Speckle Interferometry (ESPI), also known as electronic Moiré holography, is based on the same principles as that of holographic interferometry. The main difference being a change from the film to a CCD-camera (Gryzagoridis, 2001). A speckle on the surface of the object is considered to be a property of the surface. Thereby, any small rotations or deformations by the speckle can be related to the material behaviour (Sciammarella, 2003:13). An ESPI-technique was used by Martinez *et al.* (2003:525). The technique uses slight changes in the scattered speckled pattern produced by the deformation of the objects surface between two video frames to quantify deformation. The laser coherence light used to illuminate the surface, exploited the fact that speckle intensity varied on the rough surface. The method proved to be inexpensive, required little surface preparation, and provided substantial latitude for placement of source beams. The method further provided sensitivity of 0.48 lines/ μm at a resolution of 0.43 μm . Commercial systems are available from Correlated Solutions Inc. (2004). Sutton *et al.* (1999:145) focused on crack closure measurements using computer vision and a far field microscope. A random high-contrast speckle pattern was applied to the surface of the specimen. Two subsets, or in other words, two pairs of small selected speckled areas, were identified and the relative displacement used to quantify the deformation. In order to quantify the crack closure at a number of crack opening displacements, measurements were made behind the crack tip. The methodology described in this document by Sutton *et al.* (1999:145) has three distinct components:

- An imaging system with adequate magnification and minimal distortion;
- A simple Windows®-based procedure for image acquisition and image analysis; and
- Techniques for applying random high-contrast patterns on the specimen's surface.

The area of investigation was relatively small (0.5 mm x 0.5 mm) and near to the crack tip. The advantages of this technique included:

- The automation of data acquisition simplified the traditional tiresome process of measuring crack closure;
- The capability of performing measurements close to a moving crack tip, captured the local response near the crack tip (with crack closure being a highly localised event); and
- Close measurements provided better resolution in identifying the crack opening load, as a result improving accuracy.

2.5 Discussion

Most of the methods discussed in the two previous sections utilise measurements of some kind and the most important measurement in the FCGR-field is the crack length. Its use is vital in obtaining a Paris equation for a specific material. This measurement is obtained through direct or indirect, contact or non-contact methods.

In general, direct methods have the advantage that the real exact measurement is taken, whereas indirect methods require calculations to be made. Contact methods physically touch the specimen. The disadvantage of this is that the equipment may as a result of this, become contaminated by the specimen itself. Non-contact measurements have the disadvantage that they are often sensitive to material finish.

The crack length is often measured by an extensometer through the compliance method. All extensometers must perform well in any condition without disturbing the sample. Vial (2004:34) names three important features of extensometers in the selection process:

- The extensometer must be fixed on the sample without modifying the shape and surface of the sample. This is easier when using a rigid sample but not so if a softer or small sample is used;
- The integrity of the extensometer must be maintained in any environmental condition (high or low temperature) and through break, if possible; and
- The extensometer must accommodate a large extension range without losing accuracy and precision.

One of the most widely used methods, the compliance method, is used in laboratories to provide an average crack length figure. Separate calibration tests that are required in some instances and the contacting issue are two of the disadvantages. On the other hand, this

method has a relatively simple calibration procedure, no specimen size dependants and does not require the specimen to be visually accessible.

On the contrary the laser and visual based methods, which include optical microscopy, image correlation and the interferometry methods, require the specimen to be visually accessible. Optical microscopy and the like provide higher sensitivity in order to take a closer look at the surface structure whereby crack initiation can be detected. Photography and microphotography provide actual images that can be analysed after the test but lack the continuous monitoring shown by the electric potential drop and compliance methods. The electric potential drop method is well established for high temperature applications but is generally only used on metallic specimens.

The diffraction methods are expensive, often present difficulties in implementing the equipment in the test environment and require high levels of expertise. Optical correlation techniques have recently been extensively used to measure deformation. Most of these methods provide high levels of sensitivity and require high levels of experience.

The software and equipment available on the market was investigated as part of the research surrounding the CGM methods. Initially, image measurements that used contrasting markings on the surface of flat tensile specimens were thought to be sufficient (as used by Vial (2004:33)) in CGM. Measurement of the crack growth would then have to be done through a compliance method while implementing the image measurements.

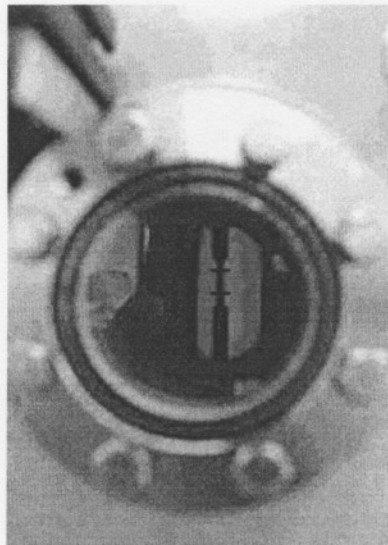


Figure 2-24: Observation window of a vacuum chamber for use with video extensometer (Messphysic, 2003).

Correspondence with one of the major materials testing companies presented a similar set-up for a video extensometer (Figure 2-24). Even though the specimen illustrated is not a CT-specimen, it showed that image methods could be used where the specimen is situated inside a chamber. Furthermore correspondence with regards to available software for CGM of a CT-specimen inside a chamber did not provide many answers. Lastly the video extensometer types on the market are quite expensive, as they require high-definition cameras and specialised software.

2.6 Conclusion

The aforementioned testing methods cover a wide range of options, but few can compare with the travelling microscope with respect to simplicity, ease of set-up and use, and versatility. Many of the older testing machines are still equipped with travelling microscopes. Unfortunately they require frequent manual operation and stoppages. This is not only time consuming and labour intensive, but stoppages may cause unwanted peaks in loading of the specimen.

Optical methods may even be the most suitable method in CGM due to their direct approach, but have not kept up with recent advances in photography. Digital photography has opened the door for image analysis almost immediately after taking a picture. The question remains: To what extent can an affordable and up-to-date optical method be incorporated in existing equipment? Therefore, it was concluded that the aim was to incorporate optical techniques and to develop a crack growth system and evaluate it for further exploitation.

This implied that the following three outcomes were required:

1. Apply a cost effective optical method combined with image analysis to find a suitable crack growth monitoring technique;
2. Evaluate the design methodology; and
3. Present an operating manual.

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CHAPTER 3 - The Design and Assembly of the Testing Facility

3.1 Introduction

This chapter describes the approach to designing and assembling of the experimental testing facility and starts with the final layout. The set-up that was designed and used was made up of the following sub-systems: An Instron 1603 Electromagnetic Resonance (EMR) machine and controller that were available, a Nikon D70 digital camera with associated software that was selected and acquired, lighting and connecting equipment and a Personal Computer (PC) that was available, as illustrated in Figure 3-1.

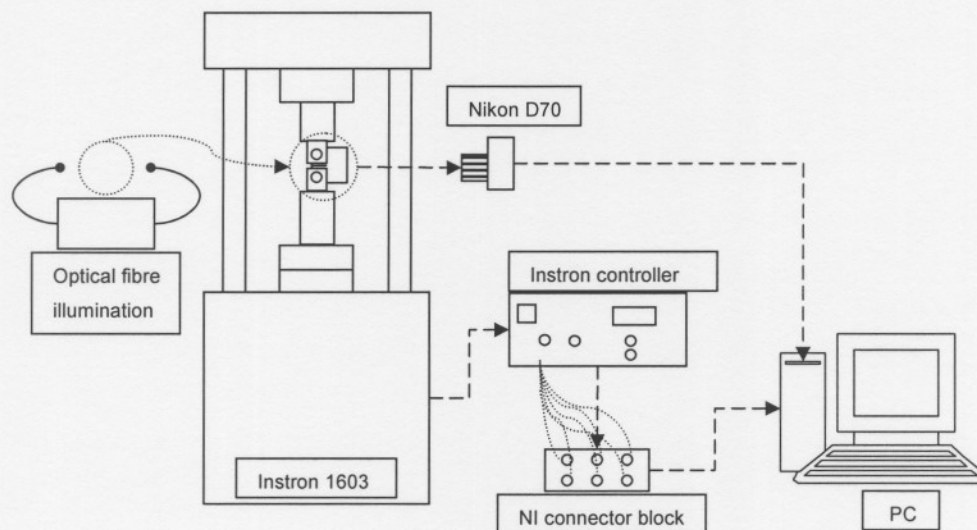


Figure 3-1: Schematic illustration of test components

The design process followed a typical systematic approach to design as outlined by Pahl and Beitz (1988:45). As the system was intended for in-house use only, the design focused on achieving the objective of monitoring crack growth propagation, as opposed to repeated testing for commercial use. The systematic process is outlined by the headings of each section and was subjected to continual upgrade and improvement.

The design process that was followed can be divided into two parts. The first part focuses on the physical design and set-up of the equipment. The second part focuses on the programming of the applicable software and is included in the programming section of the main design.

3.2 Task Clarification

A standard Compact Tension (CT) specimen is required to be subjected to a constant amplitude load where certain variables are essential to the task. The core of the design can in basic terms be described as a method that monitors the crack growth of a standard specimen in order to find a Paris equation. This requires that the crack length, a , is monitored with respect to the number of cycles, N and should provide a $\frac{da}{dN}$ value that corresponds to a ΔK value. The ΔK value is a function of the change in force, ΔP , the width of the specimen, W , the specimen thickness, B , and the crack length, a . This is presented in equation (2.1). Furthermore, the crack growth is required to be monitored through an optical method.

3.2.1 User Requirement Specification

The specification is divided into two sections, namely the set-up requirements and the problem areas.

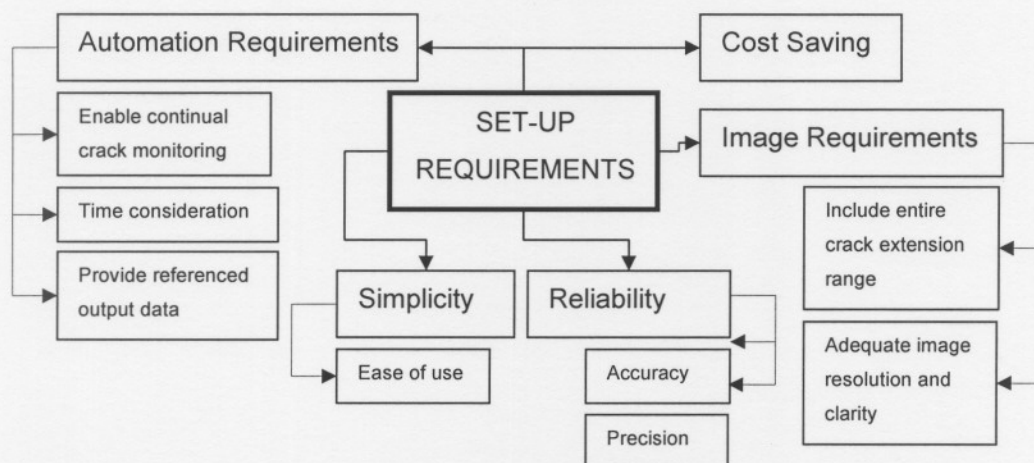


Figure 3-2: Set-up requirements of crack growth monitoring system.

The set-up requirements as illustrated in Figure 3-2 consist of five main parts which are automation requirements, image requirements, simplicity, reliability, and cost saving. The automation requirements focus on the software and hardware used to capture data continuously, to provide referenced data, and to provide information concerning the time aspect related to the time of the acquired data, the rate and how long it takes. Furthermore, the time consideration also refers to hardware-software interaction. The image requirements include the monitoring of the entire crack length so that adequate resolution is utilised to detect the crack at

all times and to increase the clarity of the image. Simplicity and cost saving are the basic needs of any design and are therefore required to be implemented. The reliability requirement is addressed by implementation of the design.

The essential problem areas are the incorporation of old existing equipment with the image equipment, and using an image set-up to find an adequate amount of information to obtain a satisfactory amount of data.

3.3 Conceptual Design

In order to achieve the required outcome, care was taken in evaluating the possible concept solutions to the problem. The design and assembly of the testing facility was a time consuming process, due to the different facets of each intertwining component which had to be taken into account, as well as the many options available on the market. The main factors that had to be considered when choosing equipment were: the components' compatibility, applicability, quality and keeping costs down to a minimum. The equipment option section focuses on the different options that were available and considered for each component.

3.3.1 Equipment Options



Figure 3-3: The Instron 1603 Electromagnetic Resonance (EMR) machine.

The available equipment included an Instron 1603 Electromagnetic Resonance (EMR) machine with controller (Figure 3-3). The controller allowed for load and frequency control and provided analogue outputs of minimum load, maximum load, dynamic load, mean load and frequency.

The Instron 1603 EMR-machine is capable of determining basic SN data, fracture toughness, crack growth data and fatigue data. It accommodates a number of test specimen types. Of interest were the CT-specimen and the frequency range (for this type of specimen it is around 100 Hz). Furthermore, it allows for constant amplitude loading (as illustrated in Figure 2-3) with a maximum of 100 kN. Until now, the CGM was done through a travelling microscope.

The data from this machine was required to be logged, in order to know at what frequency and magnitude loads were applied to the specimen at all times. The BNC-outputs from the controller therefore needed to connect to a PC. The analogue signals from the machine were required to be converted to digital signals and this was possible through a Data Acquisition (DAQ) card. Many types are available on the market and the endless options included the input/output (i/o) voltage range, the sampling rate, the i/o resolution, the number of i/o connections, and the connectivity type, among others. The connection between the DAQ-card and the BNC-cables also required a connector. Furthermore, a Compaq® Pentium 4, 1.8 GHz with 500 MB RAM was available for use.

Camera selection implies the process of choosing between different types of cameras. This process was influenced by factors such as brand names, quality, applicability, connectivity and cost. Advances in digital cameras have increased quality and simplified the process, as images can now be viewed directly, as opposed to film cameras and its time consuming development. Also, digital equipment has now become more affordable.

The first parameter in choosing a digital camera, was resolution. A high resolution camera was required as the cracks on the specimen could start as small as the width of a hair (approximately 0.1 mm). The size of the sensor determined the resolution and the price tag of the equipment. There are currently two main types of electronic imaging sensors in large scale use, that is: the Charge Couple Device (CCD) and Complementary Metal-Oxide Semiconductor (CMOS) sensor. It is claimed that both of these deliver the same quality (Tarrant, 2003:53).

A guide from National Instruments® (NI) called *Image Fundamentals* (NI, 2003:3-2) refers to a 640 x 480 pixel resolution (the resolution that a basic computer screen normally starts at) up to a 3072 x 2048 resolution for digital cameras. The price range for smaller resolution video CCD-cameras, start at about \$500 and increases up to \$32 000 for the largest. When referring to

digital cameras, two types are generally known, they are video cameras and photographic cameras. The competitiveness of digital media has now made it possible to purchase a digital Single Lens Reflex (SLR) photographic camera with 6 Megapixels (3072 x 2048) for under \$1 000 (in the US). This price relates to approximately R12 000 (Cameraland, 16 March 2004). The prices from Westplex (Westwood, 2003) for digital, colour, firewire Basler video cameras of 1.5 to 4 Megapixels are R40 000 and R118 000 respectively. When comparing the costs of a video camera and a photographic camera of 6 Megapixels it is clear that the latter is more cost effective. One drawback in choosing a photographic camera is its lack of ability to communicate with data acquisition cards in general. The lack of control means that the images can only be acquired at earlier predefined time intervals through time-lapse photography.

Lens choice was the next deciding factor. Some cameras have built in lenses with optical zoom, digital zoom, and close-up capabilities. Optical zoom is normally used for enlarging images from a distance. For this application however, the image was relatively close-up (approximately 20 cm). Digital zoom is really only an enlargement of the available image with no added enhancement. Close-up capabilities make use of specialised lens configuration that permits the field of view to be close to the lens. The SLR photographic type cameras have the option of fitting a suitable lens. SLR-like and the common types of cameras often only use auto focus; the problem with this is that the camera could focus on the wrong object.

A few guidelines from NI were followed to choosing a camera (NI, 2003:3-8): The approximate longest length of the specimen in the field of view of the camera was 70 mm. The smallest feature was estimated at 0.1 mm.

The minimum pixel resolution was calculated from:

$$PR_{\min} = \frac{l_{\max}}{l_{\min}} * 2, \quad (3.1)$$

therefore

$$PR_{\min} = \frac{70 \text{ mm}}{0.1 \text{ mm}} * 2 = 1400,$$

where $l_{\max}$ = length of objects longest axis and $l_{\min}$ = size of object's smallest feature. The value for the smallest feature was selected as a maximum value, in other words, if the smallest feature was in fact a little smaller, higher minimum pixel resolution would then be required. This minimum pixel resolution value refers to the number of pixels in one direction; therefore a 1 400 x 1 400 resolution was regarded as the minimum. The standard sizes in this range however vary between 1 280 x 1 024 (too small) and 2 084 x 2 084 (approximately 4 Megapixels).

Figure 3-4 below, shows a number of relationships between the different parameters used for determining the focal length of the lens. The following calculations made use of educated guess values in selecting the appropriate camera. Sensor sizes varied but in general three sizes are used in CCD-video-cameras to evaluate the following equation. They are 6 mm, 8 mm and 11 mm across (NI, 2003:3-8).

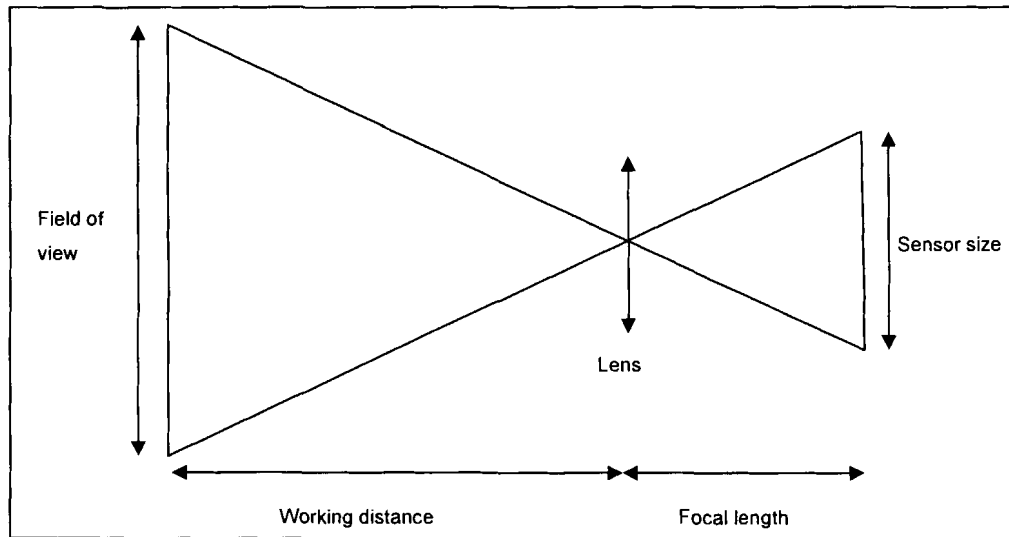


Figure 3-4: Relationship between field of view, focal length, sensor size and working distance.

For this case the field of view was taken as the width of the CT-specimen. The working distance was estimated at approximately 200 mm. Calculating the estimated focal length with the largest sensor size of 11 mm:

$$fl = \frac{ss * wd}{fov} \quad (3.2)$$

therefore,

$$fl = \frac{11 * 200}{70} = 31.43 \text{ mm}$$

where fl = focal length, ss = sensor size, wd = working distance, and fov = field of view. The field of view is generally taken as the longest length of the area of the object under inspection.

3.3.2 Concept

The concepts as illustrated in Figure 3-5 and Figure 3-6 show the conceptual layouts for the aforementioned equipment. Figure 3-5 firstly shows the Instron 1603 and the CT-specimen interaction (where a load is applied). Secondly, the image of the specimen is acquired and then simultaneously recorded and logged with the load data from the Instron 1603. Processing of

the data is subsequently required by means of image analysis and by synchronising the image data with the Instron data.

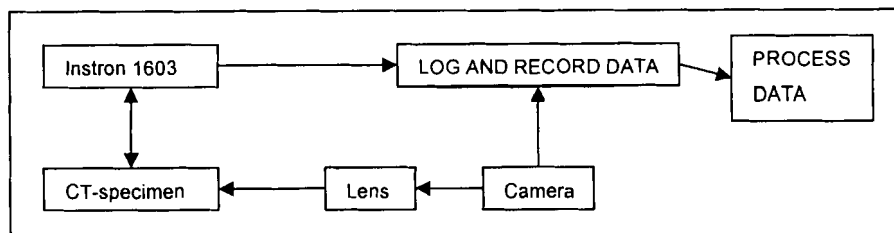


Figure 3-5: Concept 1 – Layout for CGM through an optical method.

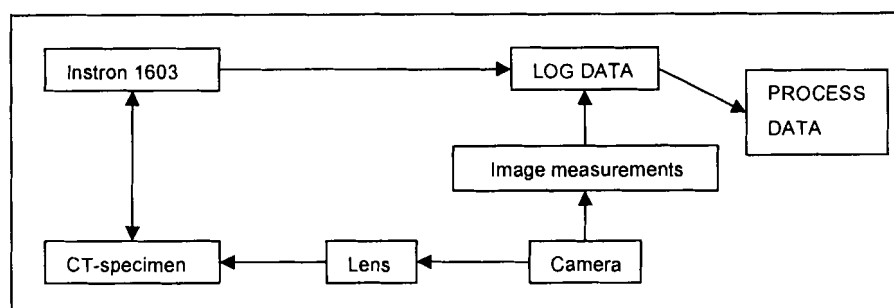


Figure 3-6: Concept 2 - Layout for CGM through an optical method.

The second concept (Figure 3-6) is similar to the first (Figure 3-5) with the major difference being that the image measurements are made through image analysis prior to logging the data. The disadvantage of this, is that image measurements are time consuming and may cause unwanted delays. The advantage, on the other hand, is that decisions can be made on the measurement before logging the data.

Ideally, image measurements were required to be made when the specimen was under maximum tension, thereby causing the crack in the specimen to be better visible. This would then require the camera to be controlled according to the maximum load. However, with the Instron 1603 operating at around 100 Hz, timing the image capture with the point of maximum tension, would have to be very accurate.

The image analysis software was required to make crack measurements. Factors to consider were time, accuracy, sensitivity and reliability. Initial thoughts concerning the measurement of the crack length focused on two main processing ideas. The first was to incorporate image correlation methods, whereby the first image would be subtracted from the current image. This

would indicate all the changes that occurred on the surface of the specimen, causing the crack to be visible. From there certain image processing techniques would enable clear measurements. The main drawback to this method is that even though small movements occur, due to constant amplitude loading on the specimen, these movements may in fact be large enough to cause lighting changes on the surface of the specimen. Subtracting one image from another would then cause twice as much noise, thereby causing many unwanted particles. It could be argued that it was possible to manipulate the order of the image processing, thereby eliminating additional particles and subtracting images, to acquire a good result. Then again, the program had to be versatile in as many ways as possible to enable good results to the user at all times. The other main consideration in this set-up was the location of the reference point from where these two images would be compared.

The second processing idea used a reference system that could also be used in the first method. It used small reference areas on which little or no deformation occurred, image processing techniques to clear unwanted particles, and standard image processes (such as threshold) to highlight the crack. The crack would then be measured from a reference point and in the direction of the expected crack growth.

3.4 Embodiment Design

The embodiment design includes the equipment selection, the software selection, the preliminary layout and the definite layout.

3.4.1 Equipment Selection

As mentioned in 3.3.1, the Instron 1603 EMR-machine and a Compaq PC were available for use. Microsoft® Windows XP™ was the PC's operating system while an extra 80 GB hard drive was obtained to facilitate the many large images (see Table 3-1), here its size was dependant on the time required for testing.

The choice of a DAQ-card manufacturer was made easy by the software, LabVIEW™, which was available for use at the North-West University. It is a product from National Instruments, as is the vision analysis software (see 3.4.2) which formed the core of the design. Connectivity between the computer and the EMR-machine was achieved by using a NI 6023E PCI data acquisition card. The data acquisition card falls in the low cost bracket of the NI components. It has 16 analogue inputs, an input range of ± 0.05 to ± 10 V, 12 bit resolution and a maximum sampling rate of 200 kS/s. The connector block, also from NI allowed for communication between the Instron 1603 and the data acquisition card. The six BNC-cable outputs attached to

the connector block from which the NI-cable attached to the NI 6023E. The order of connection is listed in APPENDIX E - Connection.

The Nikon D70 (Figure 3-7) is a low cost digital SLR-camera. At the time of purchase, the body only, sold for approximately R12 000. The other digital SLR-camera in this price and quality range was the Canon EOS 300D. Even though this camera was a bit cheaper than the Nikon, the Nikon was chosen for its higher shutter speeds and for the larger buffer capacity (Digitalreview, 2003). In addition both of these cameras have USB interfaces. Looking at similar cameras with firewire or better transfer rates, the camera features moved up to the next level together with a price increase of more than R8 000. The Nikon Capture software for use with the Nikon D70 allowed for time-lapse photography. More details about this software is given in 3.4.2. To summarise, the Nikon D70 was chosen for its 6 Megapixel resolution, direct transfer capability to the PC, the time lapse software option, wide range of sensitivity and shutter speed settings, cost saving and the option of any appropriate lens.



Figure 3-7: Nikon D70.

Lens choice was made easy by the many Nikkor® lenses available for the camera. The sensor size of the Nikon D70 measured 28.4 mm across. The initial working distance of 20 cm was changed to 15 cm to allow the focal length of 60.86 mm¹. It then followed that a 60 mm macro lens was the appropriate selection for the set-up. In addition to the lens, an AC-adapter was acquired to allow continual use of the camera.

3.4.2 Software Selection

LabVIEW was used to write the final program from which all measurements were taken. It was used in conjunction with NI Vision Assistant, while Nikon Capture provided camera control and image storage directly to the hard drive.

$$1. \quad f_l = \frac{(ss * wd)}{fov} = \frac{28.4 * 150}{70} = 60.86 \text{ mm.}$$

LabVIEW is a powerful graphical interface programming language. It is compatible with a wide range of data acquisition cards available from the manufacturer, NI. NI Vision Assistant is another program from NI. It was used to simplify the process surrounding the obtained images, analysis and programming variables. It allowed for complete image analysis with ease and implementation within the main program. Some of the NI Vision Assistant functions that were identified as useful are briefly discussed:

- *Image calibration*: Allows an actual measurement of the object to be related to the number of pixels whereby image measurements can be made in real dimensions;
- *Pattern matching*: This functionality locates previously defined templates within a greyscale picture. The advantage of this function is that the pattern is found, regardless of poor lighting, blur, noise, the shifting of the template or the rotation of the template. A score value between 0 and 1 000 indicates the accuracy where an exact match returns a score of 1 000;
- *Binary conversion*: Results from the threshold process whereby regions contain pixels with either values of 0 or 1. This in effect eliminates the "grey areas" and defines a clear-cut contrast;
- *Removal of unwanted particles*: During this functionality, spots or noise in images are removed. Depending on the number of iterations the size of these loose standing spots can be removed; and
- *Measurements in real world coordinates*: This functionality uses data from the calibrated image to relate pixel size so that measurements can be made. Furthermore, axis origin points and angles can be identified to simplify certain measurements.

The Nikon Capture software formed part of the selection of the Nikon D70. It allowed for camera settings from the PC and for the location of the image on the hard drive. Time-lapse photography allows pictures to be taken at specified intervals, as set by the user. Once an image is saved, the camera settings and capture time are recorded. When the saving process takes longer than the specified interval, the software notes a failed attempt and allows the next photograph to be taken when the saving is complete. The saving process is dependent on image size. The following table provides a guideline for estimated saving time with the given PC-set-up:

Size	Approximate file size (MB)	Resolution (Megapixel)	Approximate saving time (seconds). (May vary with PC speed)
Small	0.8	1.5	2
Medium	1.6	3.3	3-4
Large	2.9	6	8

Table 3-1: The time it takes to save an image (jpeg) to file.

Figure 3-8 illustrates the main equipment and software used in the design and assembly of the testing facility equipment. Take note that the compatibility aspect between the equipment and the software also applies to the compatibility of the different equipment.

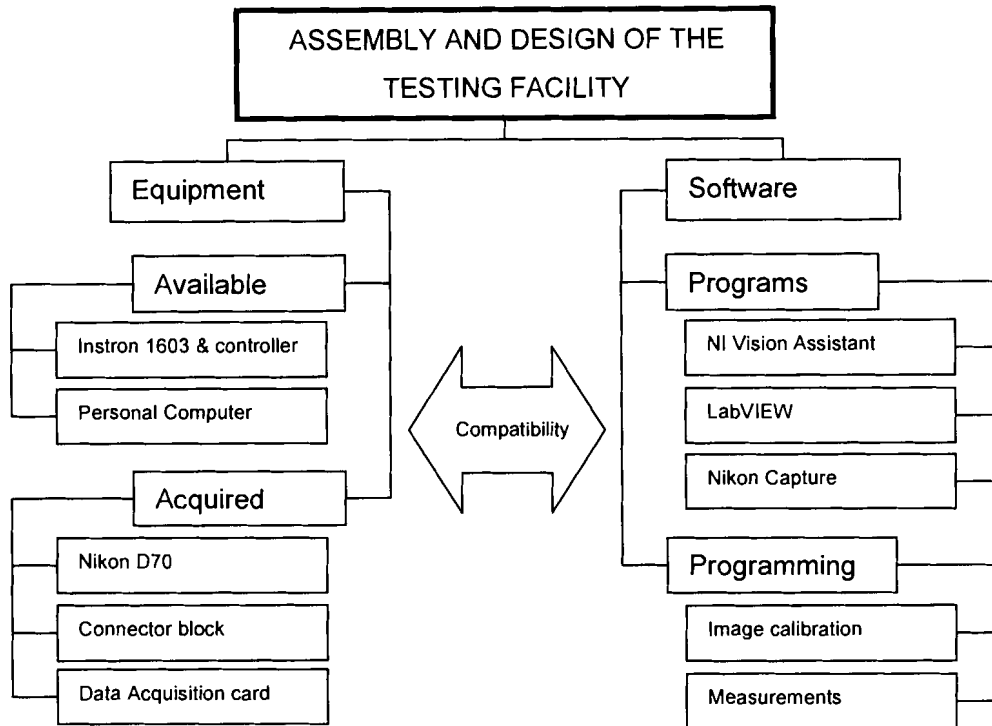


Figure 3-8: Illustration of the equipment and software and their related topics.

3.4.3 Preliminary Layout

The preliminary layout of the experiment turned out to be the same as the final layout as illustrated in Figure 3-1. It shows the CT-specimen which is constantly loaded (constant amplitude load) by the Electromagnetic Resonance (EMR) machine while the digital camera takes photographs as the specimen deforms and the crack grows. The data from the EMR-machine is then sent via the connector block to the data acquisition card. At the same time, the digital images are stored to the hard drive.

With regard to the software and processing order of the image data, as referred to by the concepts illustrated in Figure 3-5 and Figure 3-6, concept two was chosen. The camera saving time proved to be the main consideration. It allowed enough time for image measurements to be made and which, in turn, permitted images that showed no change in crack length from the previous acquired images to be deleted from the hard drive. The main advantage of this was the elimination of unnecessary hard drive storage.

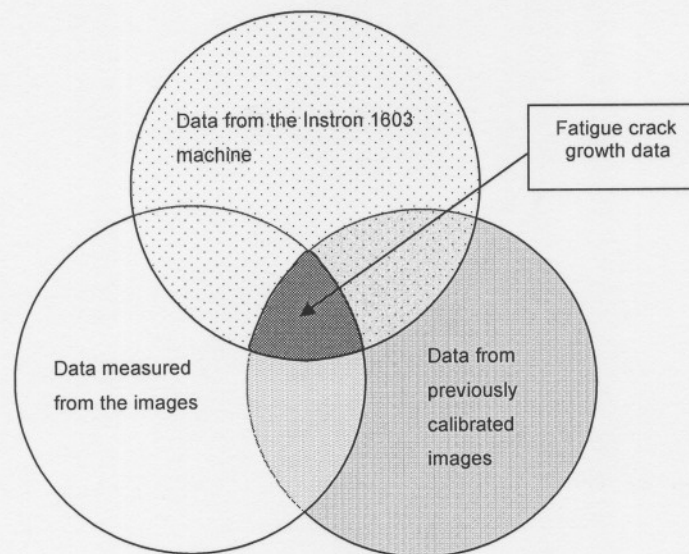


Figure 3-9: Required data for crack growth rate.

The programming aim was to provide fatigue crack growth data through three main operations as indicated by Figure 3-9. It shows the recorded loads and frequency output data from the Instron 1603 that are synchronised with the image data from the LabVIEW program. This image data is calibrated through previously physically made measurements. Together, these three main operations aimed to provide sufficient crack growth data.

3.4.4 Definitive Layout

Figure 3-10 shows the actual experimental set-up. The set-up is exactly the same as the schematic illustration in Figure 3-1.

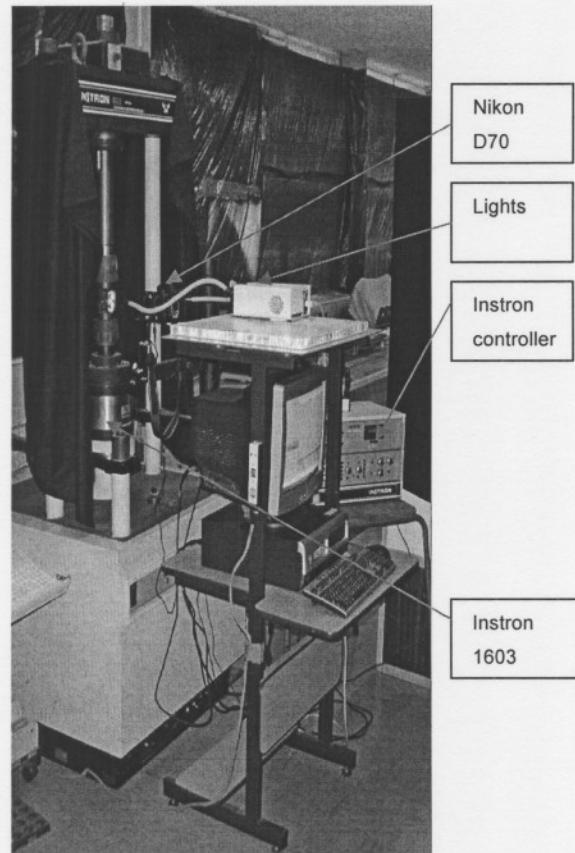


Figure 3-10: Experimental set-up.

3.5 Embodiment Design: The Set-up Requirements

The set-up requirements include the specimen, lighting and camera settings.

3.5.1 Specimen

The type of specimen that was used is called a Compact Tension (CT) specimen. Its geometry is defined by ASTM E647 (2002:11). Certain parameters with regards to the CT-specimen had to be met in order to ensure the validity of the experiment (as discussed in APPENDIX D - CT-Specimen). These included a procedure for the required surface finish of the specimen.

3.5.2 Lighting

It was found that the lighting of the specimen was arguably one of the most important factors that could influence the measurements. As all the measurements were made through optical methods, any shadow, for instance could have resulted in faulty measurements. It was for this reason that a dark room was created to minimise the effect of any reflection from external sources.

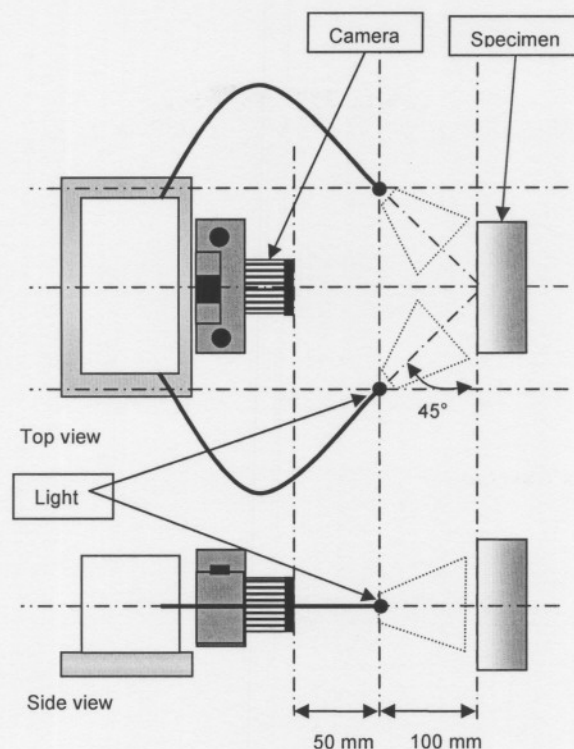


Figure 3-11: Lighting for CT-specimen.

The second important light factor was the illumination of the test specimen. This was achieved through two sharp optical fibre lights, angled at approximately 45° to the specimen (as illustrated in Figure 3-11). The lights were parallel positioned to the horizontal and 100 mm from the specimen. This was an essential factor in minimising the change in light on the specimen when the machine was in operation.

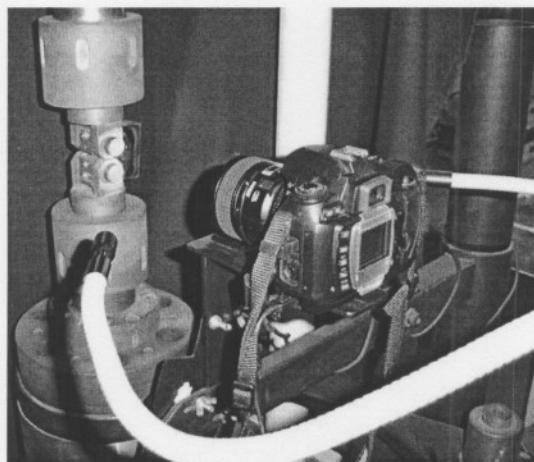


Figure 3-12: Picture of the actual camera and layout of the lights.

The aim of the lighting was to provide clear images as well as to provide enough illumination to the areas under investigation. For the lighting set-up, Figure 3-11, illustrates the distances and angles that were used. Figure 3-12 shows the actual layout of the lights.

To be more precise, once this set-up was completed, lighting on the specimen resembled that of Figure 3-13. The left light illuminated the notch mouth opening (Figure 3-13 (a)) of which the upper and lower corners were initially used for calibration and later for optional CMOD-measurements. Horizontal alignment was very important on this side, due to the shadows which were created by the grips. These shadows could easily have been cast over the crack growth area if the light was misaligned. Figure 3-13 (b) shows the right light does not cover the whole notch, but rather the whole expected crack growth area. Figure 3-13 (c) shows the left and right lighting on the specimen. Take note that the right side of the light falls just inside the specimen, as not to illuminate the edge of the specimen.

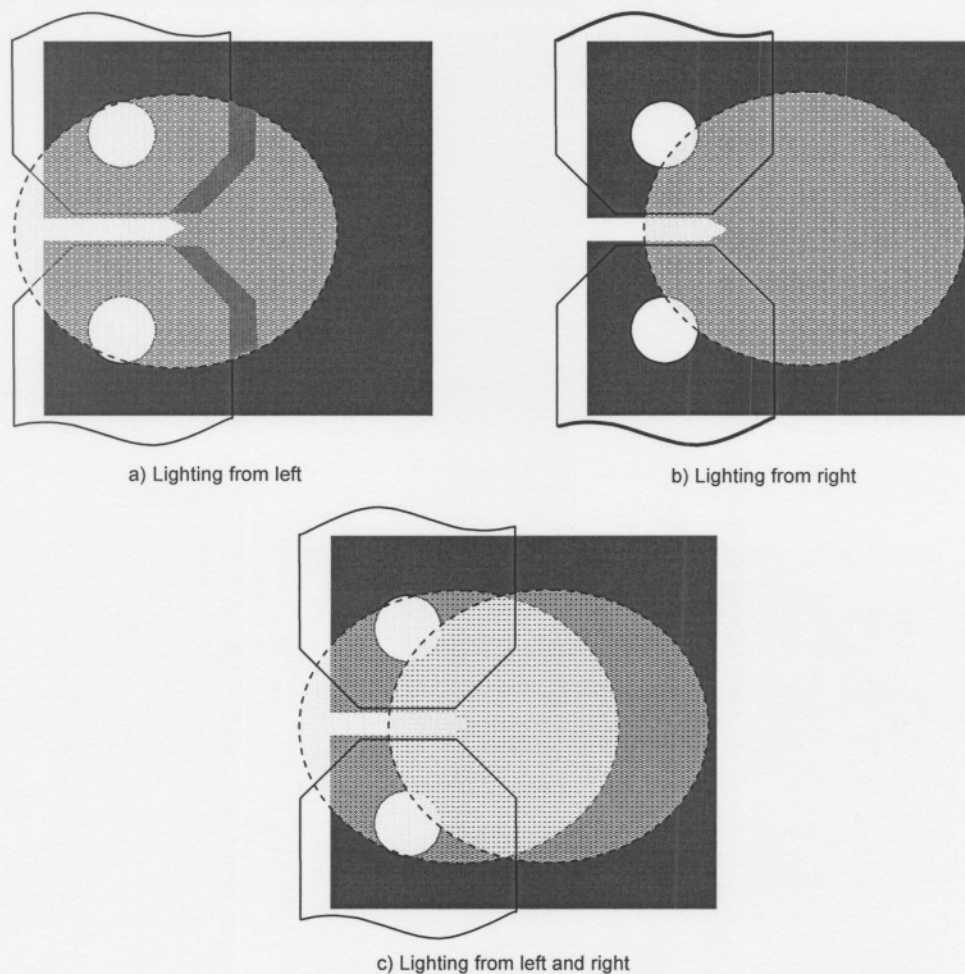


Figure 3-13: Required lighting condition.

3.5.3 Camera Settings

Camera	Nikon D70	Metering mode	Multi-Pattern 1/320 sec – F/5.6
Type	JPEG (8-bit) Fine	Exposure compensation	+0.3 EV
Image size	Large (3 008 x 2 000)	Sensitivity	ISO 1600
Lens	60 mm F/2.8 D	Optimise image	Normal
Focal length	60 mm	White balance	Auto
Exposure mode	Manual	AF mode	Manual
Flash Sync mode	Not attached	Hue adjustment	0
Colour mode	Mode la (sRGB)	Saturation	Normal
Tone compensation	Auto	Sharpening	Auto

Table 3-2: Camera settings.

There were a number of camera settings, however many different combinations were possible. Those that work best, with regard to the conditions, are briefly discussed. Table 3-2 shows the camera settings that were used in the actual test.

If the sensitivity setting is higher, pictures are more likely to be subjected to noise in the form of randomly spaced brightly coloured pixels. Higher sensitivity allowed for lesser amount of light required to make exposure, allowing for higher shutter speeds or smaller apertures. Higher shutter speeds enabled still images of subjects in motion. The maximum sensitivity setting of ISO 1600 was chosen with a shutter speed of 1/320 s and an aperture of f/5.6. The large image size of 3 008 x 2 000 (6 Megapixel) was used throughout the test. Furthermore, the Capture software allowed the images to be saved in the base directory (more about this in 3.6.2.1).

3.6 Embodiment Design: The Main Program

The main program was programmed to be straightforward and easy to use. In addition APPENDIX A - Operating Manual, provided adequate instructions on how to operate the program.

3.6.1 Calibration

An important aspect of the design was the calibration. The image calibration that was used is briefly discussed and was implemented as outlined in APPENDIX B - Procedure for Image Calibration. The calibration procedure used the NI Vision Assistant program to reach the required outcome by running the Calibration.scr file. The calibration procedure required that a picture of the CT-specimen, which included the CMOD and the portion of the specimen that included the entire expected crack length, was taken. It furthermore required that a physical

measurement was made in order to relate the number of pixels to real measurement values. The CMOD measurement at pre-tension was used for this task. Furthermore pattern recognition techniques were used to identify the crack initiation position, and the upper and lower corners of the CMOD. Markings were scribed onto the surface at the pattern matching locations to assist pattern recognition. Figure 3-15 illustrates the patterns and their respective saved locations. It shows three red arrows pointing to three positions on the CT-specimen. They are:

- The upper corner of the CMOD - UpperCorner.png;
- The crack initiation position - CrackCorner.png; and
- The bottom corner of the CMOD - BottomCorner.png.

The calibration procedure did not only generate these three pattern files but an image calibration file was also created. This file included the information whereby, all the pixel measurements that were made during the test, were related to real measurements in millimetres. The image file is identified in Figure 3-15 with a green arrow. It is:

- The calibrated image file - CalibratedImage.png

The image validity of the points that were identified according to APPENDIX B - Procedure for Image Calibration was checked by a NI Vision assistant file called CheckImage.scr (find its location in APPENDIX G - Software (CD)).

3.6.2 The LabVIEW Program (CGM.vi)

The LabVIEW program was written to incorporate all the data from the different sources, to log the data, and to be able to process and correlate it afterwards. Its programming was made easier by the NI Vision Assistant program as all the vision related programming data was converted from a NI Vision file (.scr) to a LabVIEW (.vi) file. After conversion, it still required a fair amount of work. First of all, it was required that all the interfaces available to the user had to be straightforward and accessible, enabling the beginner to operate it. Then it was checked as the conversion process sometimes lost information along the way (as was the case with this development). Once this process was completed, full programming commenced. The structure of the program resembles that of Figure 3-14:

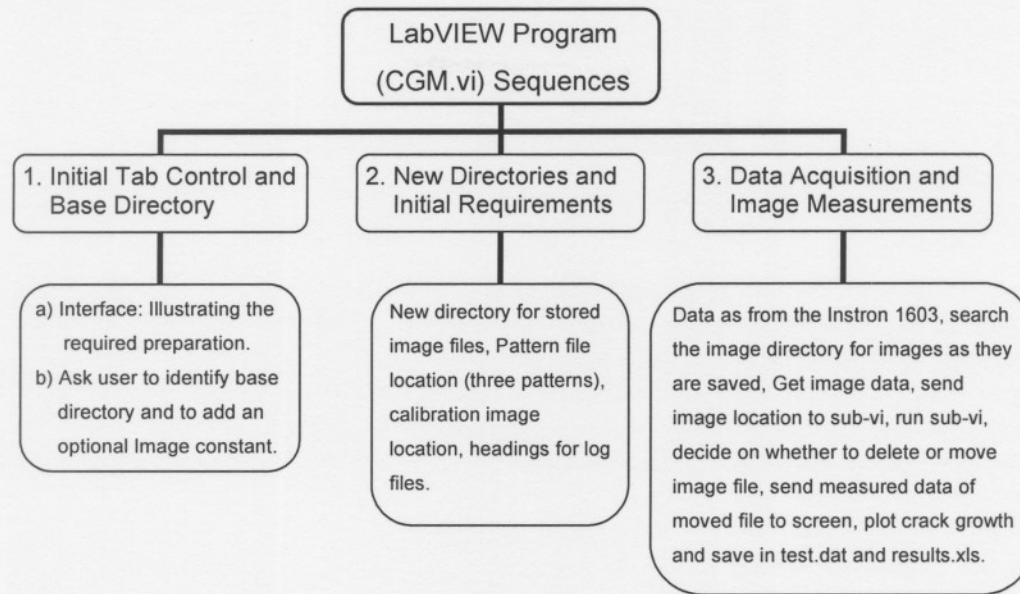


Figure 3-14: Order of program actions.

The following discussion may require the reader to follow the printed program in APPENDIX C - LabVIEW Programs. The program was made up of three sequences as indicated by Figure 3-14. The program was written to complete the initial tab control and base directory sequence (1) before the next sequence started and so forth. It then follows that the new directories and initial requirements sequence (2) was then followed by the data acquisition and image measurements sequence (3).

3.6.2.1 Tab Control and Base Directory (Sequence 1)

The first sequence was programmed to interact with the user. Figure 3-15 below, illustrates the actual LabVIEW interface which the user sees when the program (CGM.vi) initialises. It is the first of two, where the first is referred to as the initial tab and the second as the information tab. The initial tab was structured to provide the necessary information to the user prior to running the CGM.vi file. Figure 3-15 shows which programs should be executed before continuing with the program. It refers to the before mentioned calibration images and their locations. In addition an optional image constant value can be entered on the initial tab. This option was added to the initial tab at a late stage of the design. It's functioning allowed for the elimination of some of the surface noise on the specimen if the specimen preparation required it. The default value for this optional input was set to 0. This value is experience related but some guidelines were outlined in APPENDIX B - Procedure for Image Calibration. The image constant value ranges from 0 to 255. During the program operation, this value would then be

deducted from the pixel values. In effect, the input value was set as a limit whereby all (dark) grey pixel values below this value were set to 0 (black).

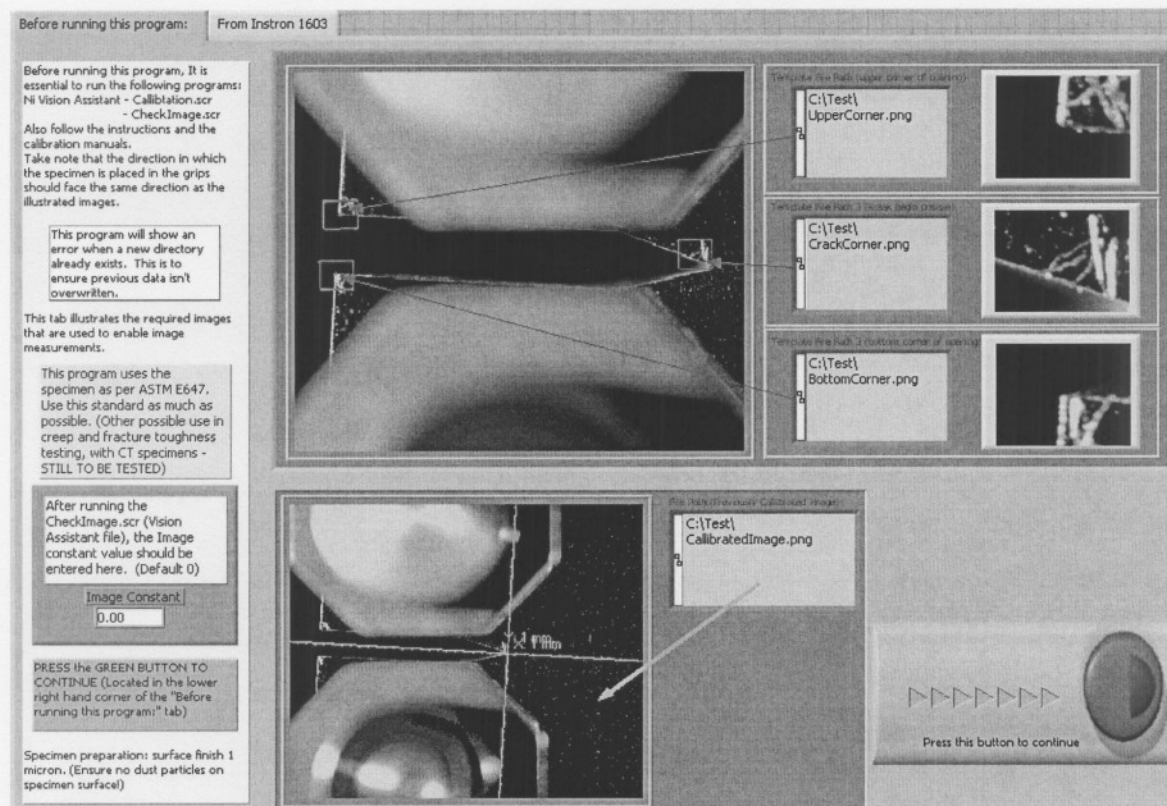


Figure 3-15: The initial tab.

The green button located in the bottom right-hand corner of Figure 3-15 was placed on the initial tab to allow the user sufficient time to read all the information. Figure 3-16 shows the actual LabVIEW window that appears when the green button is pressed. It is called the user input check. It was created to remind the user of the essential connections to the Instron 1603, the warm-up period of the machine, and of the setup of the camera and its software. As a safety procedure the program was set to stop if any of these reminders were not checked by the user.

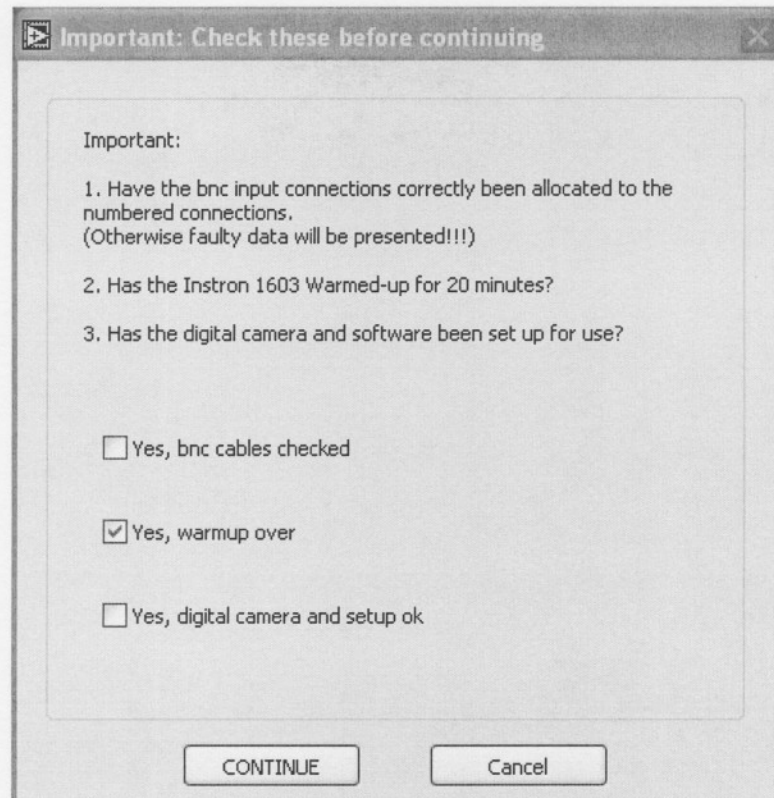


Figure 3-16: User input check.

3.6.2.2 New Directories and Initial Requirements (Sequence 2)

The programming of the second sequence included a few interface windows which required the user to firstly select the base directory from where all image processing was made. As a precaution to overwriting previous image data, the automatic creation of two subdirectories in the base directory was dependant on whether the base directory had already contained the two directories or not. If not, the program was set to end. These two directories that were mentioned are: *movedfiles* and *deletdfiles*. These directories subsequently provided the location for the image files that had already been processed. The final version of this program only used the *movedfiles* directory to store those images which provided adequate data (more about this in 3.6.2.3 Sequence 3.1). The excess images were set to be deleted. APPENDIX G - Table G 1 contains the location of a modified version of the main program where the deleted images are stored in the *deletdfiles* directory.

In order to obtain the location of previously defined pattern images and the calibrated image as in the calibration process (3.6.1 & Figure 3-26), a sub-routine was written to ask the user to identify their locations. This was programmed to be the last time that any inputs would be required from the user prior to post-processing.

After all the initial requirements, the focus was shifted to the interface with the user. This is the information tab (Figure 3-17) which was programmed to be displayed, once the green button of the initial tab (Figure 3-15) was pressed. It can be seen from Figure 3-17 that the information tab provides information on the relevant parameters. This figure also shows three grid displays where curves of the actual data are displayed during a test. Firstly, the top grid was used to display the crack length *versus* time. It made use of the values of the table (in the centre of Figure 3-17) to draw all the crack length points that showed an increase from the preceding point. The other two grids were used to display the frequency of the test machine and the loads that were applied. The information tab furthermore contained a stop button with which the program could be ended by the user. Below the stop button, two indicators are shown. The first light (green) was set to light up if the data from the Instron 1603 was saved. The second indicator was set to light up when the program was waiting for a image file from the camera.

A white section with the heading “Data from all images (test.dat)” as indicated in Figure 3-17, allowed the user to view all the measurements that were made on the images. This displayed information, which included the image measurement irrespective of whether the image file was kept or deleted, was saved in a file called test.dat with applicable column headings.

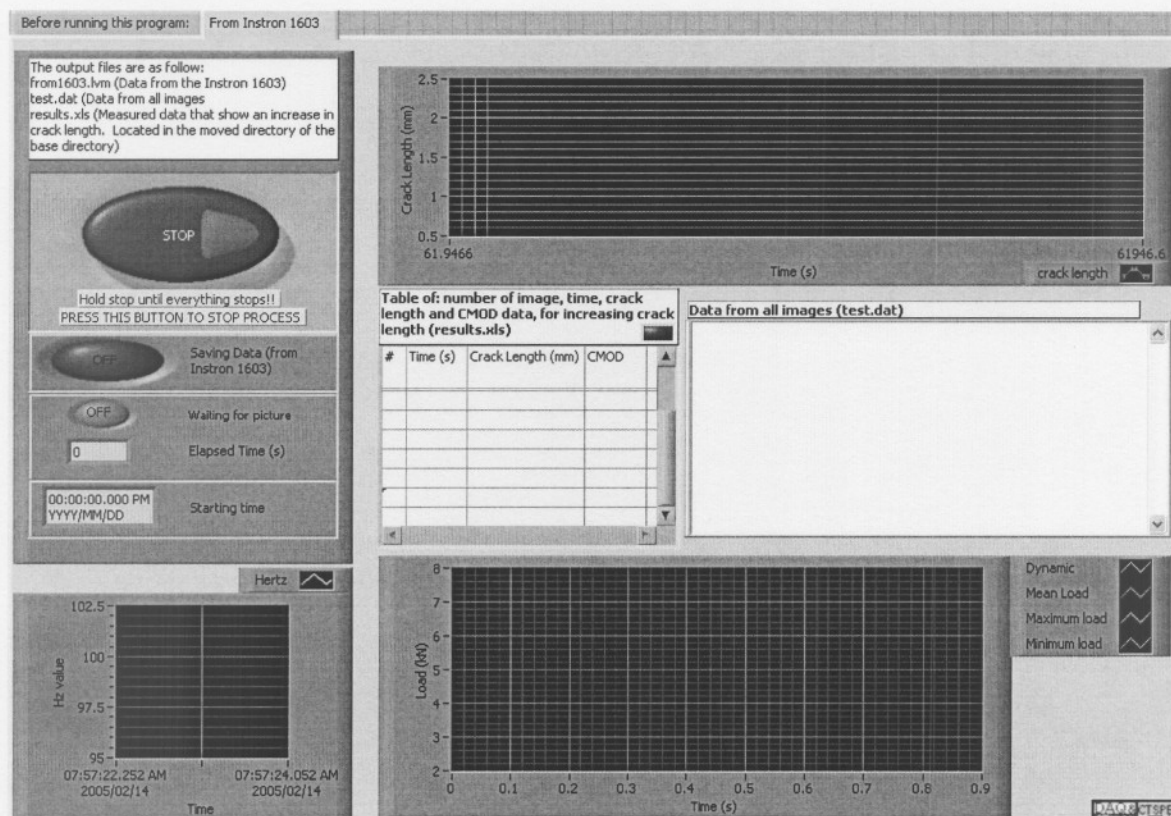


Figure 3-17: The information tab.

Additionally, the information tab shows information relating to the output files.

3.6.2.3 Data Acquisition and Image Measurements (Sequence 3)

Up to now, the discussion of the programming focussed on the user interfaces and the required inputs. This section is the main part of the program. It was made up of two while loops (While 3.1 and While 3.2) that were programmed to run concurrently. The first was written to facilitate the data acquisition and the second to enable the image analysis. A LabVIEW function allowed for the start time (in seconds) to be logged as soon as this sequence started. This enabled valid referenced data.

While 3.1

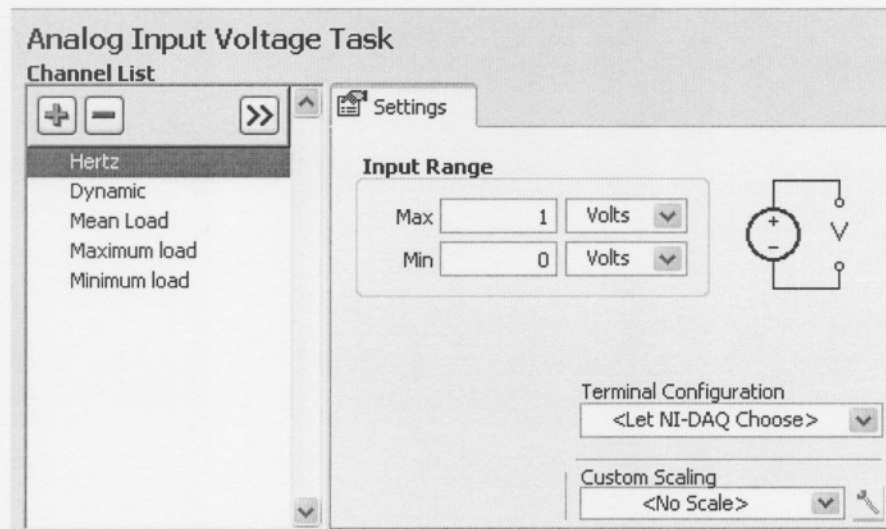


Figure 3-18: DAQ assistant function.

The data from the Instron 1603 was acquired through the DAQ assistant function of LabVIEW. It allowed for input ranges and settings (Figure 3-18). These settings were set according to the outputs from the Instron 1603. Through the outputs of the DAQ function, it was possible to display the load and frequency values on the information tab and to write the data to a LabVIEW measurement file (from1603.lvm).

While 3.2

This while was made up of two sequences (Sequence 3.1 and Sequence 3.2). The first sequence focused on the process of obtaining and analysing the image, while the second sequence included the process of recording and presenting the data and deciding on whether to keep or delete the image.

Sequence 3.1

This sequence consisted of a while loop, some basic operations and a sub-vi. The while loop was programmed to search for a .jpeg (image) file in the directory as specified by the user (see 3.6.2.2). If it existed, the while loop would end, otherwise it continued until such time. Some of the additional basic operations of this sequence included sending the location and name of the picture in progress to the sub-vi, in order to compare its crack length with that of the preceding one, and to display the measurements on the front panel.

The Sub-vi

A sub-vi is really a LabVIEW file being called within another and uses the sub-vi as a black box where certain inputs deliver certain outputs. The sub-vi, called CTSpeclmage, was mainly created with the aid of NI Vision Assistant. The aim of the sub-vi was to measure the actual crack length. Figure 3-19 shows the inputs on the left and the outputs on the right for CTSpeclmage.vi. The required inputs to produce a result are indicated as: the location of the image, pattern matches 1, 2 and 3, the calibrated image location, and the default angle of the calliper. The outputs shown are: the angle of calliper, crack length and the CMOD. The same in- and outputs can be seen on the front panel (Figure 3-20). In addition, Figure 3-20 shows some guidelines on the front panel of the sub-vi assist the user. The front panel was only visible to the user if it was used on its own; otherwise, it was hidden within the main program.

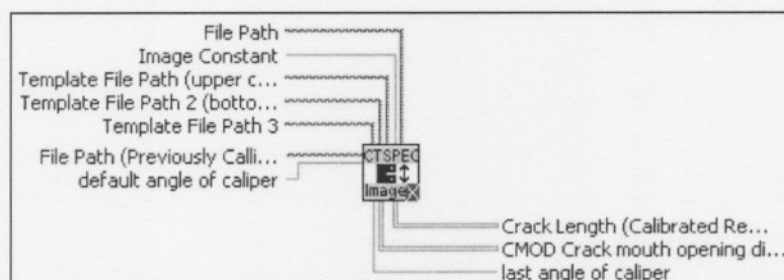


Figure 3-19: Inputs and outputs of the sub-vi CTSpeclmage.vi.

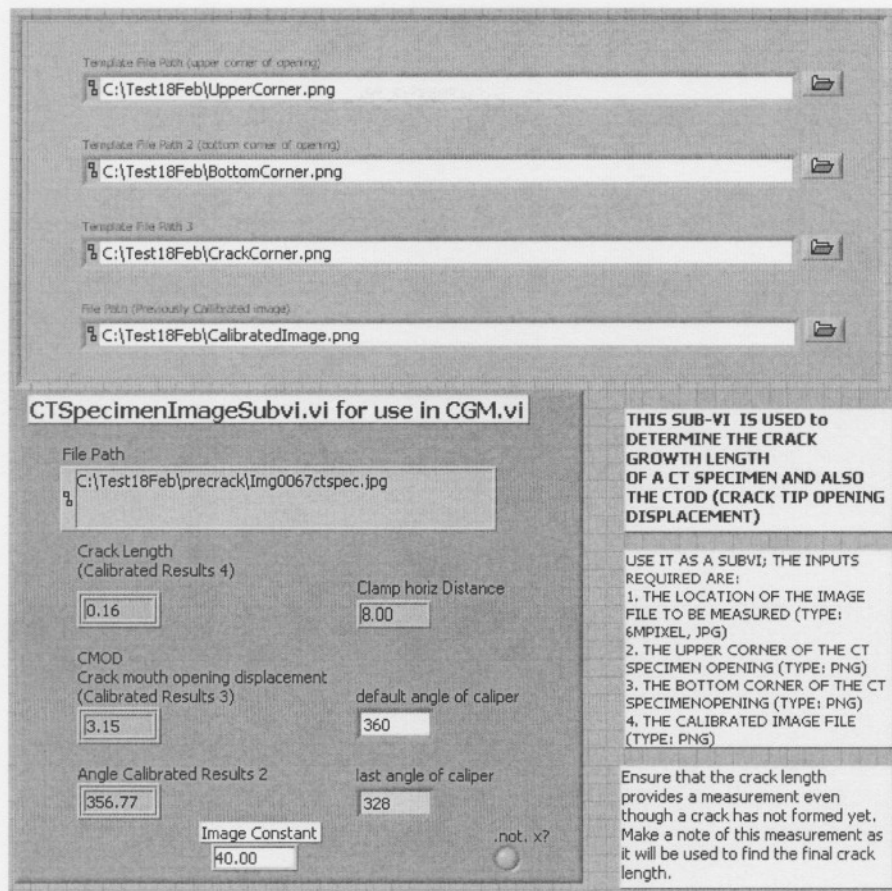


Figure 3-20: CTSpeclImage.vi front panel.

As the sub-vi was the main part of the design, special attention is given to explain the rationale behind the different aspects thereof. This method has somewhat evolved from the initial working model, mainly due to sensitivity and contrast issues, as the smallest measurable (the crack width) proved to be as small as 0.07 mm.

Contrast was mainly dependant on lighting conditions. However, the contrast aspect of the image programming required a number of considerations before the image capture process started. This needed the identification of certain parts of an image as well as the continuous clarity of the image. The visibility of the crack essentially formed the basis of the measurement. Due to the fact that the crack depth varied as the crack progressed, the crack was not visible from one end through to the opposite side. If this was true, the contrast shadows in the crack would have been better defined and would have provided clearer contrast. Consequently another route was followed. Instead of looking for shadows, the intensity or luminous areas were identified.

Naturally, the crack growth rate is dependant on the material type, but the hardness and toughness elements should not be disregarded. For instance, a tool-steel (K450) was initially pre-cracked and monitored by an initial version of this program (as illustrated in Figure 3-21 & Figure 3-22). The pre-crack proved to be difficult to determine, due to the minute fracture thickness. This led to a realisation that the program's sensitivity had to be improved, in order to enable the identification of the actual crack.

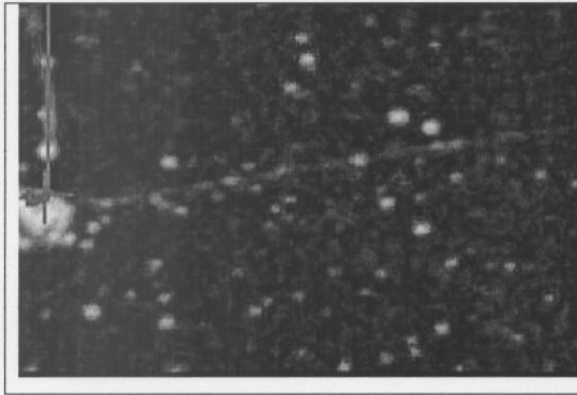


Figure 3-21: Fine crack for K450.

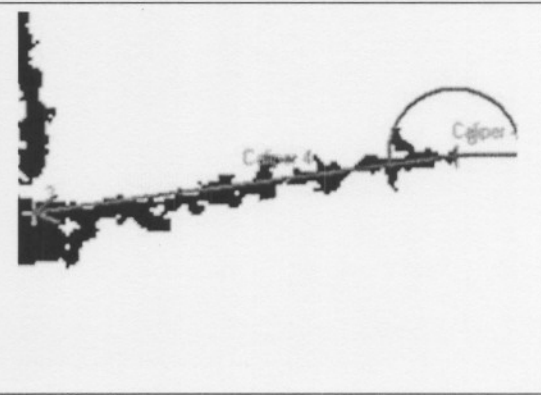


Figure 3-22: Processed image for the fine crack of K450.

The images in Figure 3-21 and Figure 3-22 show a fine crack at a length of 2.17 mm. It is clear, by means of a comparison between the images in Figure 3-22 and Figure 3-24 below, that the contrast achieved by the latter is much better than the first than the first, mainly, due to crack thickness difference. The same set-up was used for both of these examples but the material varied.



Figure 3-23: Crack length for mild steel.

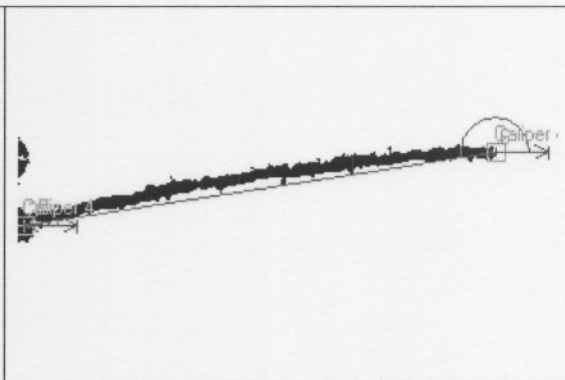


Figure 3-24: Processed image for the crack length of mild steel.

The figures of the images above (Figure 3-23 and Figure 3-24) show a clear defined crack at a length of 4.75 mm.

The method that was used is not the only solution to the problem, as many of the functions available that were used could be changed and still produce a good result. This method was a conservative approach that eliminated all the additional spots, provided that these spots had been left after a surface finish of $1\text{ }\mu\text{m}$. This meant that if any spot was identified as part of the continual crack, it would not cause significant measurement errors.

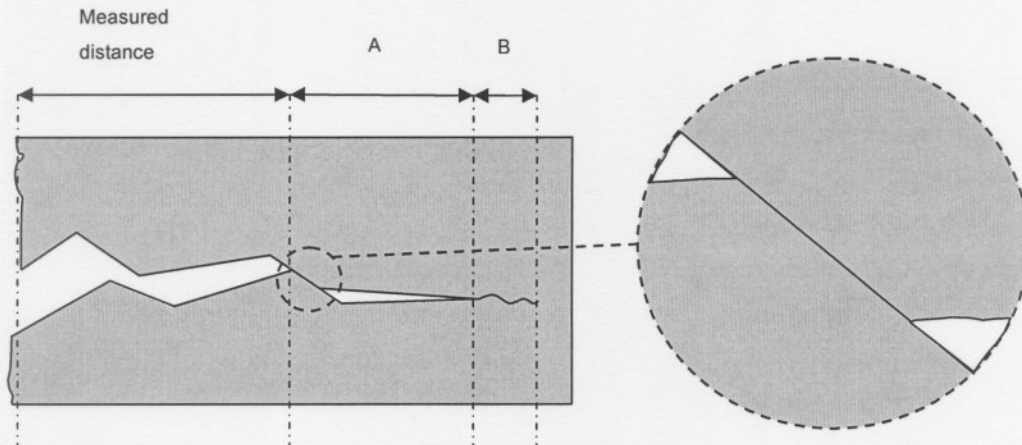


Figure 3-25: Crack length measurement.

The crack was measured where a continuous line existed from the measurement starting-point. This had the following drawback: in certain conditions, the crack might have been measured shorter than its actual length. This was as a direct result of the mechanical action of the acting forces, causing the crack to be more opened or more closed depending on the force direction. This meant that even though a crack existed, the crack was not clearly visible. Figure 3-25 is a representation of a typical crack in compression causing the crack to close at the encircled position. The image analysis would, firstly, only measure the indicated "measured distance" because the crack closure creates a very fine crack (enlarged area) that is not thick enough to be identified when the opposite sides press together. The portions of "A" and "B" in Figure 3-25 that would be identified by the program would be regarded as big spots on the surface as they are not connected to the "measured distance". In other words if a crack was "broken" then the end section would not be taken into consideration. It is for this exact reason that the saved measurements, only take the maximum measured value into consideration. For instance, if the illustration (Figure 3-25) had been in tension, a measurement would have been made that included the measured distance (distance A and B) provided B is clear enough. The next discussion uses the terminology as defined in the IMAQ Vision Concept Manual (NI, 2003: 3-1 – 3-8).

Icon	General function	Specific use	Icon	General function	Specific use
	Read image file	As is		Calliper	Mid-point, angle, distance (crack length and CMOD)
	Extract colour plane	Intensity		Auto threshold	Entropy
	Subtract Image Constant	Custom value		Remove particles	Seven iterations
	Pattern matching	Used for three patterns		Fill holes	As is
	Look up table	Exponential logarithmic		Clamp	Horizontal

Table 3-3: General functions and icons used in LabVIEW and IMAQ Vision Concept Manual (NI, 2003: 3-1 – 3-8)

Table 3-3 shows the LabVIEW functions that were used by the sub-vi. The following steps were used in the following order:

- *Read image file*: This operation opened the image file for editing.
- *Extract intensity colour plane*: IMAQ Vision required the image to be defined as a colour space when images are processed (NI, 2003: 1-13). The function allowed the possibility of extracting, red, green, blue, hue saturation, intensity, luminance, or the value plane of a colour image into an 8-bit grey scale image. For this instance, the luminance was extracted, as it showed the best results (NI, 2003: 3-11).

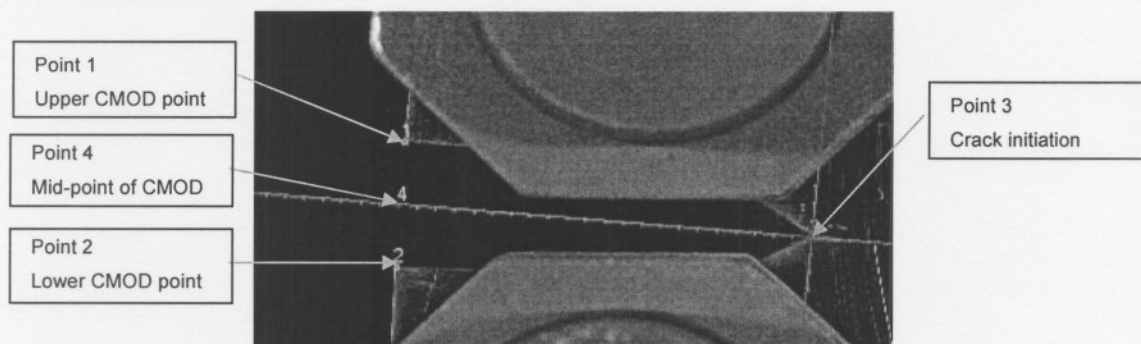


Figure 3-26: Reference points on the image.

- *Subtract image constant*: This step was the latest addition to the sub-vi. It used a value as identified by the user (see guidelines in APPENDIX B - Procedure for Image Calibration) to eliminate all image values below this value. This allowed for less noise from the specimen surface.

- *Pattern matching 1, 2 and 3:* The previously defined images (.png-files) were now recognised on the image that was used and the specified points were used to create reference points (points 1 to 3 – see Figure 3-26).
- *Exponential look up table:* This function increased the contrast in bright regions and decreased the contrast in dark regions.
- *Logarithmic look up table:* This function increased the contrast in dark regions and decreased the contrast in bright regions. One may think that this and the preceding steps eliminate each other but this is not the case. The order of the exponential and logarithmic look up tables has a similar effect than that of deducting a constant value. However, in effect, the bright areas are brighter and the darker areas darker. The effect is more apparent when the darker areas start out with a dark grey colour and the bright areas with a light grey colour.
- *Mid-point calliper:* This calliper set a new point (4) in the middle of the line connecting points 1 and 2 (Figure 3-26).
- *Angle calliper:* The line connecting the crack initiation position and the mid-point was used to measure the angle to the horizontal plane in order to turn the coordinate system. This function was added to allow for a rotational movement of the specimen or misalignment of the grips.
- *Set calibration information:* The previously acquired calibration image, related the appropriate number of pixels to the actual measurements.
- *CMOD-calliper:* This calliper measured the crack mouth opening displacement through the identified point in pattern matching 1 and 2. This measurement can in future still be used to incorporate a compliance method.
- *Auto threshold entropy:* This operation eliminated the “grey” areas, as the image was converted to a black and white image (red and black). The entropy method was generally independent of lighting conditions. Of all the different standard threshold methods available, this method gave the best results.
- *Remove particles:* To avoid confusion and error readings, small particles were removed. The small particles were those that stand alone. The process used seven iterations to provide a result.
- *Fill holes:* This function filled the small holes in the image. It did not really serve any purpose except for cosmetic consideration.
- *Clamp horizontal:* This horizontal clamp (or grid) was used to measure the distance between the previously identified point 3 and the end of the crack. It was able to rotate five degrees in each direction. The rotation was dependent on the previous calliper angle measured. It, furthermore, identified a new point that indicated the end of the

crack. The size of the clamp was kept constant throughout. Its position was initially determined by the position of point 3.

- *Crack length calliper.* This calliper measured the distance from the original identified point 3 to the new point, at the end of the crack, as identified by the horizontal clamp.
- *Calliper angle.* The line that connected point 3 with the end of the crack point was used to measure the angle of this line to the horizontal line.

The rest of the operation included consideration for the angle of the calliper, deleting the image in the memory, and sending the results back to the main program. As mentioned before, the calliper angle varied by five degrees both ways. If for some or other reason the angle from the previous image was greater than these limits, a default value of 0 was sent to the clamp. The images in the memory buffer were deleted after measurements had been made. Furthermore, the results were sent to the front panel (information tab) of the main LabVIEW program.

Sequence 3.2

The second stacked sequence was made up of a case structure and numerous small operations. The case structure used input from the previous sequence in order to decide on whether an image should be moved or deleted. The criterion for this operation was based on the previous determined value of the crack length. If this value was smaller than the current value, the image file was moved, otherwise it was deleted. The rest of this sequence was devoted to the display of the image measurement results on the information tab. Also, the measurements were saved in the different files.

3.7 Embodiment Design: Post-processing Programming

In post-processing, two methods were used to obtain a graph for the crack growth rate. They are the Secant method and the incremental (seven point) Polynomial method.

The Secant method used in the data reduction is the most sensitive of all the methods used (see ASTM E647, 2002:26). The method was chosen for precisely this reason. When sensitivity is high, it is much easier to detect any irregularities in the data.

$$\left(\frac{da}{dN}\right)_{\bar{a}} = (a_{i+1} - a_i) / (N_{i+1} - N_i) \quad (3.3)$$

where

$$\bar{a} = \frac{1}{2}(a_{i+1} + a_i) \quad (3.4)$$

Equation (3.4) was used for ΔK determination.

The following equations were used for the Polynomial method:

$$\hat{a} = b_0 + b_1\left(\frac{N_i - C_1}{C_2}\right) + b_2\left(\frac{N_i - C_1}{C_2}\right)^2 \quad (3.5)$$

where

$$-1 \leq \left(\frac{N_i - C_1}{C_2}\right) \leq +1 \quad (3.6)$$

$$\text{and} \quad C_1 = \frac{1}{2}(N_{i-n} + N_{i+n}) \quad (3.7)$$

$$\text{and} \quad C_2 = \frac{1}{2}(N_{i+n} - N_{i-n}) \quad (3.8)$$

$$\left(\frac{da}{dN}\right)_{\hat{a}_i} = (b_1 / C_2) + 2b_2(N_i - C_1) / C_2^2 \quad (3.9)$$

Equation (3.5) was used for ΔK determination for the Polynomial method.

ASTM E647 (2002:8) recommends that the data be evenly distributed along the x-axis (ΔK). With regards to the method used, the captured data was irrespective of the distribution of the ΔK value and only limited by the camera processing and saving time of the pictures. This has its limitations of course. With reference to materials that have a quick crack growth rate, a low load is advised in order to obtain enough data to produce the required results.

The basic operation of the post-processing method is not discussed, as it comes directly from ASTM E647 (2002:27). The programming that was used, is available in APPENDIX C - LabVIEW Programs.

3.8 Documentation

3.8.1 Experimental Modus Operandi

Running a test was made easy by the aforementioned user interface displays of the LabVIEW programs. More detailed instructions on the operation of the program can be found in APPENDIX A - Operating Manual.

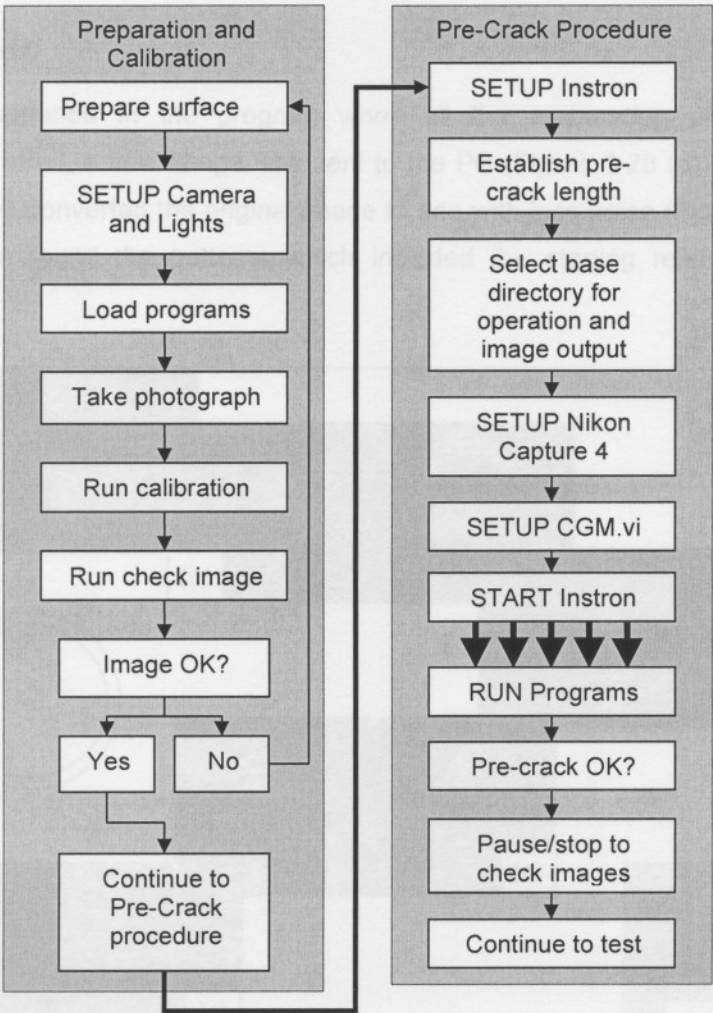


Figure 3-27: The procedure for running the test.

Figure 3-27 shows the steps that were followed for preparation and calibration, together with the pre-crack procedure. On the left, the preparation and calibration procedure is straightforward and little explanation is necessary. The Procedure for Image Calibration (APPENDIX B) was followed when calibrating an image. On the right, the pre-crack procedure may generally vary for different situations but the structure should look similar. Take note that the “START Instron”

and "RUN Programs" steps in the pre-crack procedure were executed with the least amount of time wasted between these two steps.

3.9 Conclusion

What actually happened in the program when all the preparation and calibration was completed? First of all, a new image was sent to the PC (Figure 3-28 (a)), from there certain image manipulation converted the original image to one with less noise (Figure 3-28(b)). Next, pattern recognition found the patterns which included the starting reference point (Figure 3-28(c)).

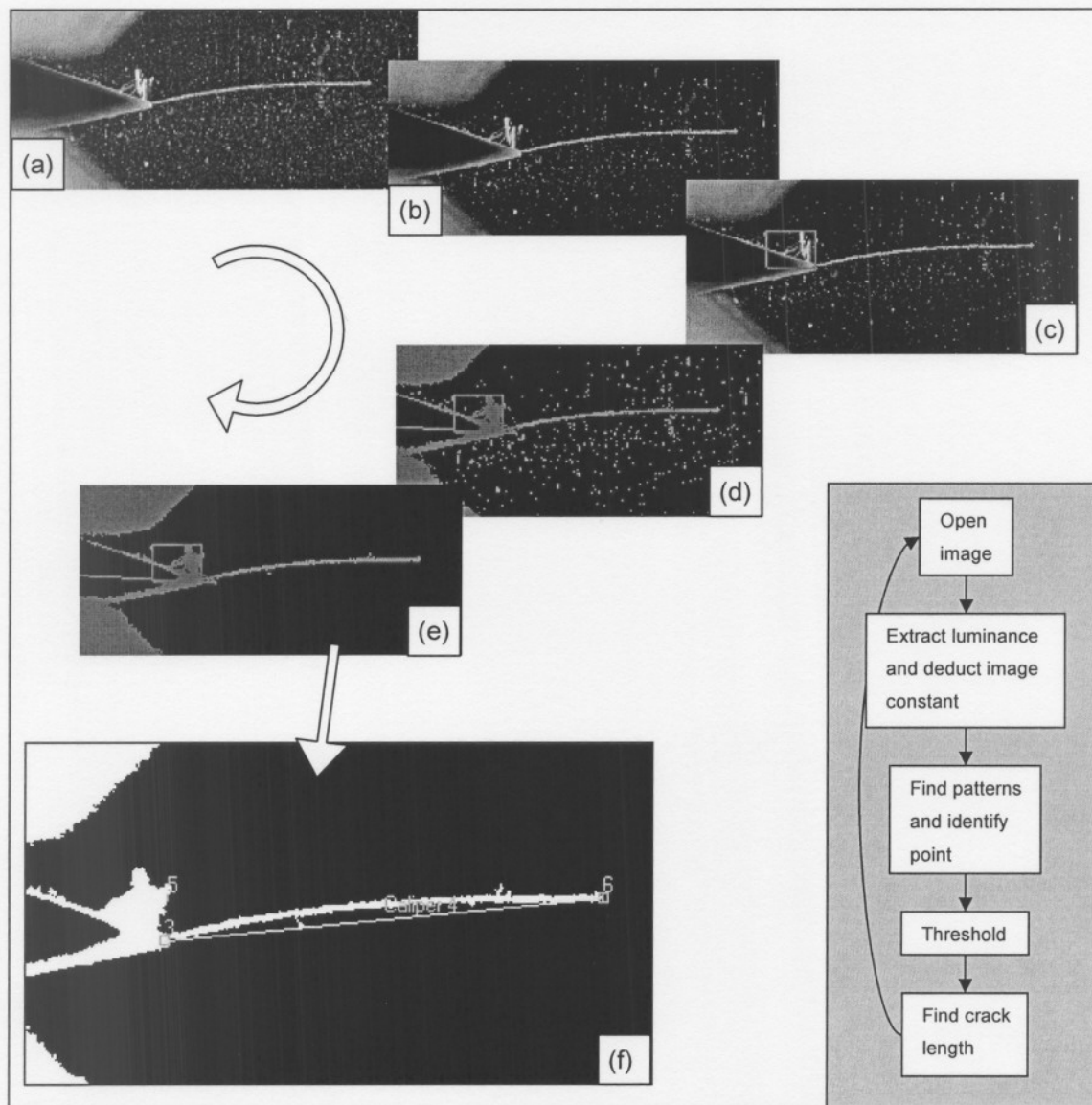


Figure 3-28: Simplified sub-vi operation.

Then the threshold function applied a 1(red) or a 0(black) value to the pixels (Figure 3-28 (d)). Excess detached particles were removed before measurements took place (Figure 3-28 e). Figure 3-28 f) shows how the measurement of the crack length was made. This process was executed approximately every eight seconds.

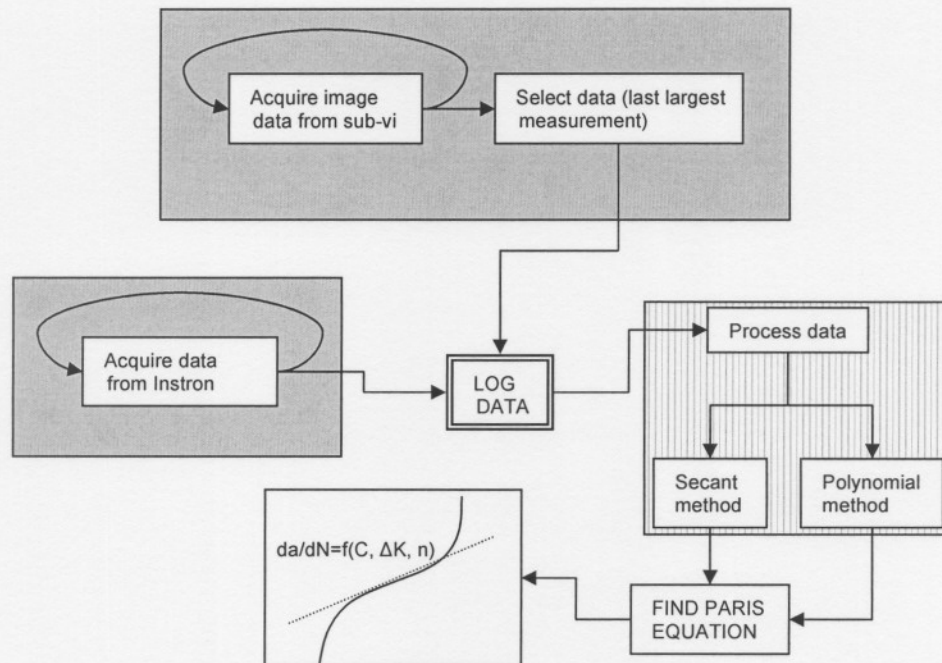


Figure 3-29: Simplified illustration of program operation.

Figure 3-29 shows a simplified illustration of what happened when the program was executed. The two main processes (indicated by the grey background) were carried out simultaneously in order to log the data from the Instron and the data from the sub-vi, continuously. Using the logged data, the post-processing created a graph of the crack growth rate *versus* the change in the stress intensity factor, by means of the Secant and Polynomial methods. Afterwards, a fit through the linear part of the fitted line revealed the Paris equation.

3.10 References

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CHAPTER 4 - The Experiment

4.1 Introduction

The aim of the experiment was to illustrate, that a digital image analysis method can be used to obtain adequate crack length data in order to find a Paris equation for a specific material. The following experiment made use of the experimental testing facility of CHAPTER 3.

4.2 The Specimen and Loading Considerations

The theory mentioned here can be found in section 2.2 and ASTM E647 (2002). The ASTM E647 standard forms part of LEFM. It requires that apart from the geometrical parameters, the following equation has to be satisfied:

$$(W - a) \geq (4 / \pi)(K_{\max} / \sigma_{YS})^2 \quad (3.1)$$

Here, the W and a parameters are the same as earlier, while the $K_{\max}$ -value is determined by equation (2.1) with the exception that $P_{\max}$ replaces ΔP . This implies that the $K_{\max}$ -value is a function of the maximum load, $P_{\max}$, the geometry values and the appropriate crack length (a). Loading considerations were not specified by the test requirements and therefore, a load estimate had to be made. In order to keep equation (3.1) valid for most of the test duration, the equation was critically evaluated: The left side of the equation is only dependant on the change in the crack length (a), as the width of the specimen (W) is unvarying. The right side of the equation is required to be smaller or equal to the left side, therefore a number of curves were drawn in order to establish the values for the variables that influence the validity of equation (3.1).

Prior to establishing the curves, the experimental variables had to be established: The specimen used, was made of mild steel. To be more specific, the yield strength (σ_{YS}) for SABS 1431 Grade 300WA is 300 MPa, commonly referred to as mild steel. The steel contains 0.22% C, 1.6% Mn and 0.5% Si (Highveld Steel, 2005). The specimen procedure that was used is presented in APPENDIX D - CT-Specimen. The same appendix also illustrates the standard specimen size configuration. According to ASTM E647 (2002), all sizes are dependent on the measurements made from the centre line of the holes to the longest end of the specimen (W). The mild steel specimen was scaled in relation to the size of the pin diameter used in the Instron 1603 machine and within the standard boundaries. The critical dimensions of the specimen were as follows: $W = 50$ mm, $B = 12.5$ mm, $a_n = 10$ mm and $h = 3.13$ mm. The geometry of the

mild steel specimen is presented in APPENDIX F - Additional Test Data. Furthermore, the test was conducted in laboratory air at room temperature.

Figure 4-1 shows four curves and a straight line. The straight line (blue) indicates the W - a value for increasing crack length from 0.01 m to 0.035 m. The four curves represent the $(4/\pi)(K_{\max}/\sigma_{YS})^2$ -term for the same increase in crack length but with different maximum loads. The maximum loads that were used to create these curves are: 10 kN for the black line, 8.26 kN for the dark blue line, 8 kN for the red line and 6 kN for the green line. The minimum load, that was kept constant at 4 kN for all of the aforementioned curves, did not influence the load estimation. The straight line (W - a term) forms the boundary which indicates the maximum value for the $(4/\pi)(K_{\max}/\sigma_{YS})^2$ term. It then follows that if a crack length of approximately 0.026 m is reached for the case when $P_{\max} = 10$ kN (black line), the data above the linear line will be invalid. In order to achieve valid data for the crack length up to approximately 0.0275 m, the maximum load applied, was therefore required to be below 10 kN and above 6 kN

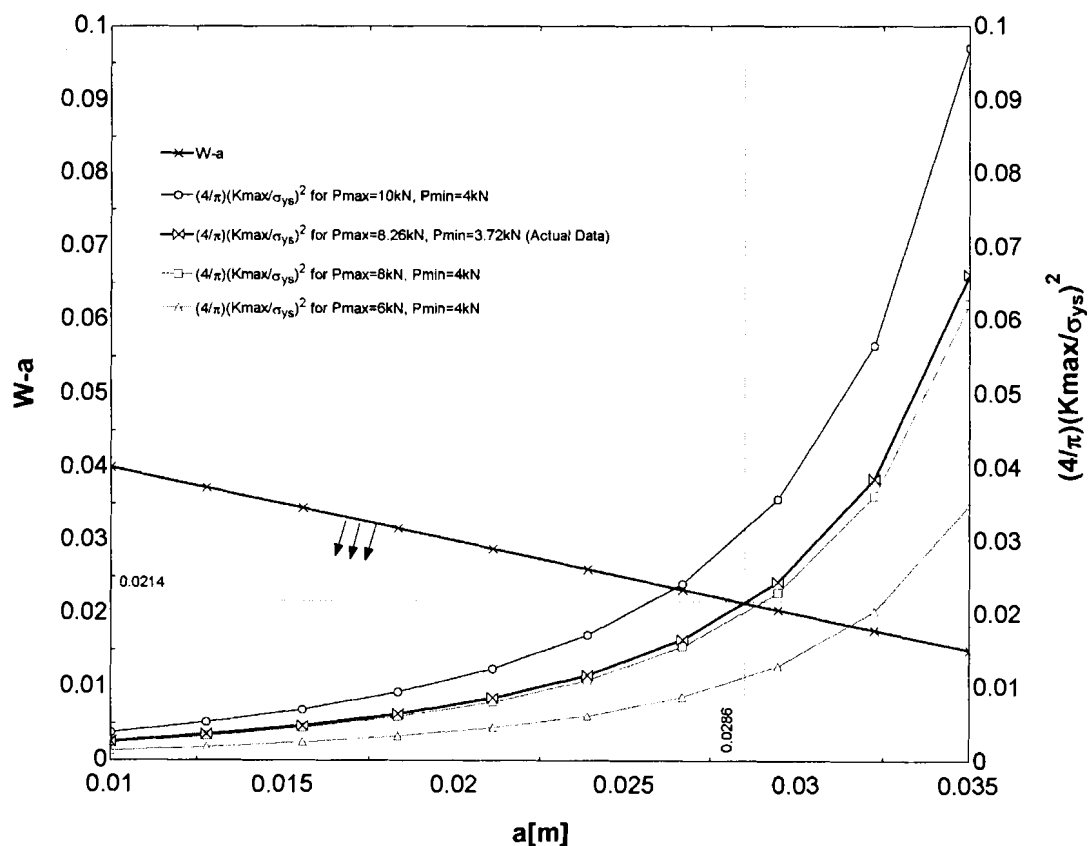


Figure 4-1: $K_{\max}$ boundaries for crack propagation through test.

The constant amplitude load applied for the test was set to $P_{max} = 8$ kN and $P_{min} = 4$ kN for the upper and lower limits respectively. This represents a load ratio (R) of 0.5. The Instron 1603 does not allow for frequency settings, but operates around 100 Hz for CT-specimens. The test procedure followed is outlined in Figure 3-27. ASTM E647 (2002:5) provides a number of options relating to pre-cracking. For the specimen in discussion, the same forces and conditions were applied to the pre-crack and to the rest of the test.

4.3 Test Results

The loads achieved during the test varied somewhat from the initial load mentioned in section 4.2, but still remained within the allowable boundaries. The effective load varied slightly, mainly due to stoppages for verification purposes. These did not cause any significant peak or valley in the constant amplitude load cycle. The actual load data with respect to the K_{max} -values is represented in Figure 4-1 by a dark blue curve. The loads applied were $P_{max} = 8.26$ kN and $P_{min} = 3.72$ kN. Using these values, a load ratio of $R = 0.45$ was obtained. It follows from Figure 4-1 that the data from the test would have been invalid if the crack had propagated to a length of greater than 0.0286 m (as indicated by the intersection of the straight line (blue) and the actual load curve (dark blue)). The test results were logged in three files, they are: test.dat, from1603.lvm and results.xls.

Figure 4-2 is a real time software (LabVIEW) representation of the crack length vs. time. It is clear that the crack growth was not continuous. The main reason for this is that the EMR machine was stopped periodically to make physical crack growth measurements for verification purposes. This caused a time delay interval, where no new image measurements by means of the LabVIEW software were added, as indicated by the bigger yellow blocks in Figure 4-2. In order to eliminate these data delays, some data manipulation was required in order to represent true values. The smaller blocks indicate a quick stoppage for the checking of images with regards to lighting.

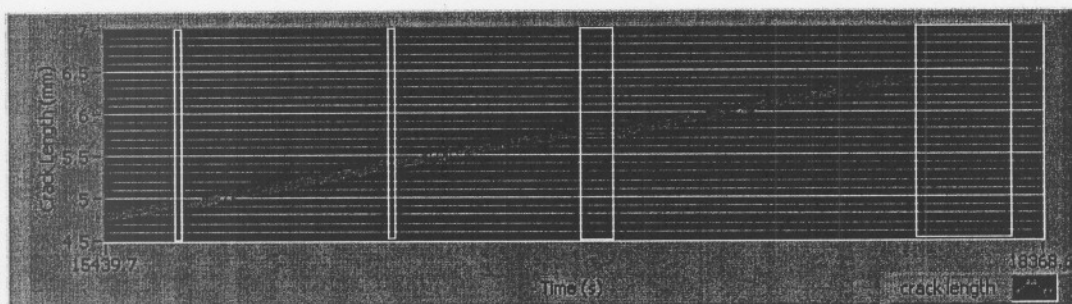


Figure 4-2: Real time LabVIEW representation of the actual crack length vs. time.

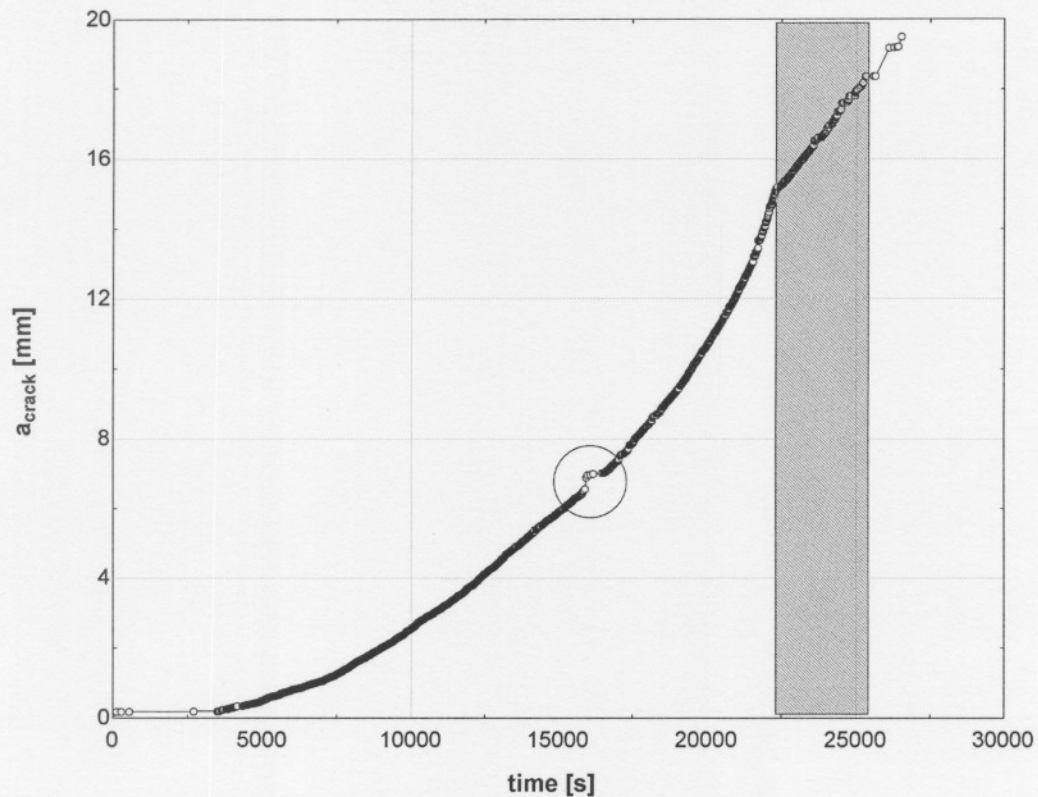


Figure 4-3 Crack length vs. time with indicated problem areas.

Figure 4-3 illustrates the crack length vs. time at which the crack extended from initiation until the end of the test. The illustrated a_{crack} -parameter refers to the length as measured by the software. It was used to calculate the true value of a . Where:

$$a_{n1} = a_{correct} + a_n \quad (3.2)$$

and then

$$a = a_{crack} + a_{n1} \quad (3.3)$$

The correction parameter, $a_{correct}$, can in most cases be ignored, due to its small value. For more detail refer to ASTM E647 (2002:11) and APPENDIX B - Procedure for Image Calibration. In this case the value for $a_{correct}$ was -0.17 mm. It then follows from equation (3.2) that $a_{n1} = 9.83$ mm. Figure 4-3 shows that the rate of change in crack length was initially slow up to around 3 000 s but then increased at an exponential rate up to about 22 000 s.

From an image acquisition perspective the test ran smoothly, except for one incident (at $a_{crack} = 6.58$ mm) as indicated by the encircled area in Figure 4-3. In this case the

measurements made by the LabVIEW program were faulty, due to reflection problems on the surface of the specimen. This is indicated by the following figures:



Figure 4-4: Cause of a faulty measurement.

Figure 4-4 (a) indicates the actual view of the crack and it shows the reflection (light grey) to the right side of the end of the crack that caused an error. Figure 4-4 (b) shows the gradient colour scheme where better definition of the crack and other particles is obtained (for illustration purposes). The small white particles indicate surface markings and the white line indicates the crack, while the red particles show parts of the reflection that are touching the end of the crack. Figure 4-4 (c) illustrates the threshold image where the lines indicate the faulty measurement. Figure 4-4 (d) shows the image without any of the unwanted speckles from where measurements are made, but it also shows the faulty measurement. Take note that the section of the crack, as indicated in Figure 4-4 (a) to (d) shows a part of the actual crack length. To put these images in perspective, the crack in the images is approximately 2 mm in length and 0.14 mm wide. The error measured 0.35 mm more than the true value. Figure 4-3 shows that for the duration of the test, the rest of the measurements were not influenced once the crack grew past the error length, the trend continued as expected.

Figure 4-3 also indicates a hatched area after approximately 22 000 s. This change in the crack growth rate is due to load settings that had to be adjusted as the dynamic forces could not be transferred by the Instron 1603 at that time. This was mainly due to the magnet air gap that was required to increase to achieve the required loads. From there on it was decided to operate at the following loads: $P_{max} = 6.84$ kN and $P_{min} = 3.75$ kN at 94.46 Hz. This gave a load ratio of $R = 0.54$. The data of this area was used for verification purposes but disregarded for post-processing to obtain a Paris equation.

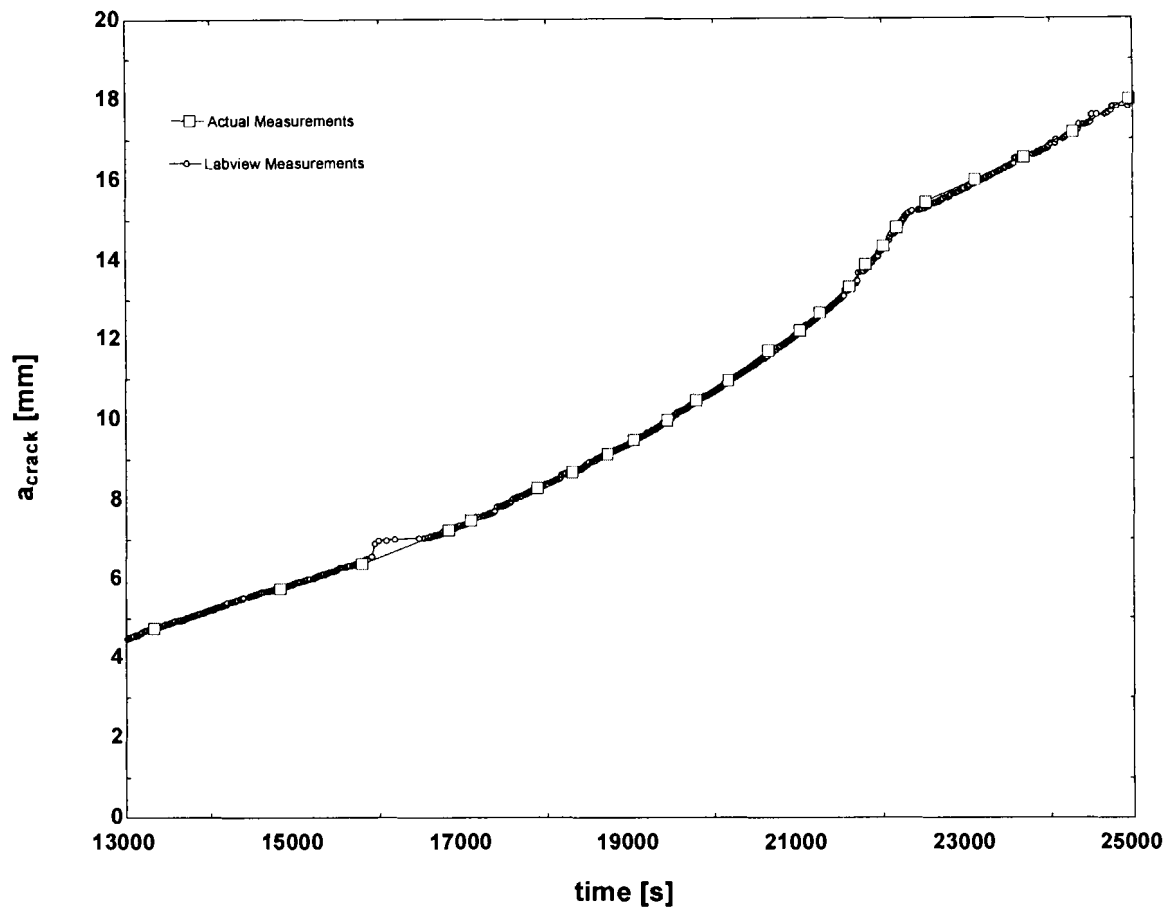


Figure 4-5: Actual measurements and LabVIEW measurements.

Figure 4-5 shows the actual points that were physically measured and plotted on the results line produced by the LabVIEW measurements. These measurements were made on the actual images, whereby a digital vernier was used to measure the actual crack. The images were larger than real life and accordingly the vernier measurements were scaled by using a known measurement as reference. Measurements, made through LabVIEW, were verified at approximately every 0.5 mm from a length of 4.75 mm to 17.99 mm. It is clear from Figure 4-5 that the actual measurements and the LabVIEW results fit very well.

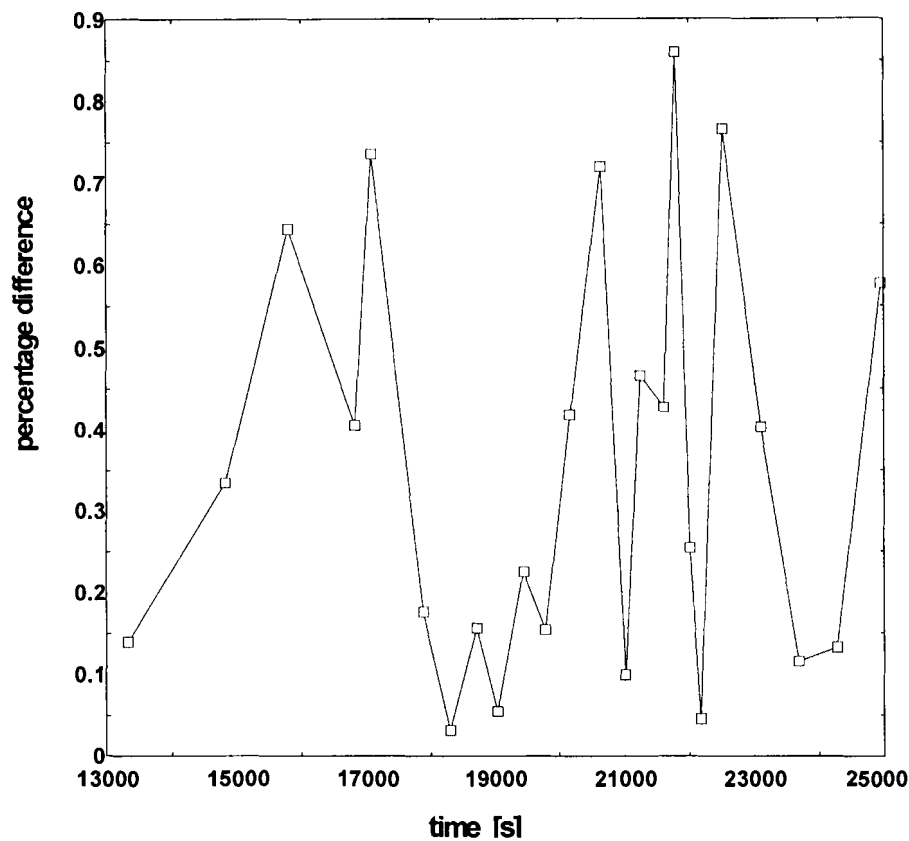


Figure 4-6: Percentage difference from LabVIEW data to actual data.

Figure 4-6 shows the percentage difference from the LabVIEW data and the actual data. The LabVIEW data for the 24 measured points did not vary with more than 0.9% from the actual measurements.

It is fair to say, from the above results, that the measurement system was valid.

The error that was made, as previously mentioned, was corrected by using the images that were supposed to be deleted. The LabVIEW program normally deletes the excess images, but this functionality was replaced, as a backup, with a function that keeps the deleted files in a separate folder. To evaluate these faulty images, the image constant value had to be increased to make accurate measurements.

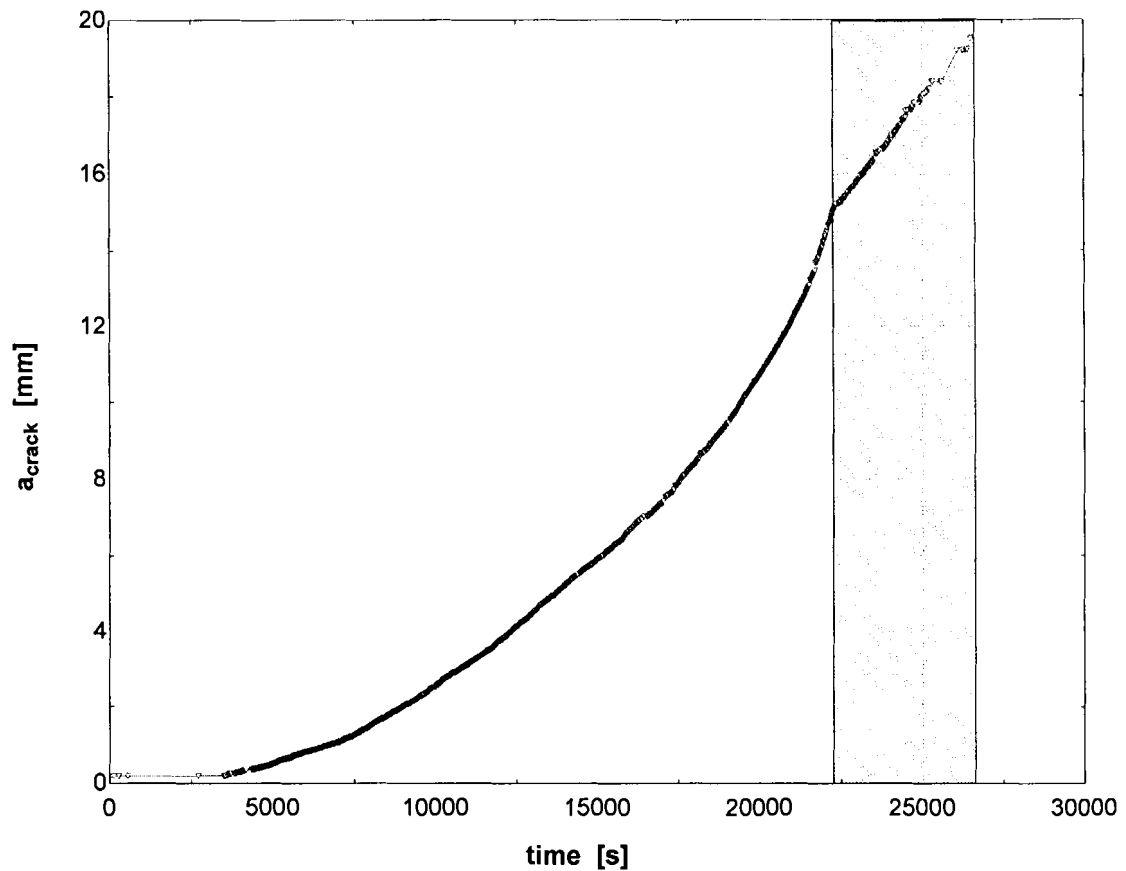


Figure 4-7: Corrected crack growth propagation data.

Figure 4-7 shows the crack propagation rate with the corrected error. The hatched area is disregarded for the post-processing while the rest clearly shows a continual line with an exponential trend.

The following chapter deals with the post-processing of these results.

4.4 References

ASTM E647-00. 2002. *Standard Test Method for Measurement of Fatigue Crack Growth Rates*. 42 p.

HIGHVELD STEEL. 2005. [Web:]

<http://www.highveldsteel.co.za/marketing/files/SANS1431300WA.htm> [Date of access: 30 January 2005]

CHAPTER 5 - Processing of Results

5.1 Introduction

ASTM E647 (2002:8) recommends that the change in crack length is evenly distributed for change in ΔK . As the crack growth was monitored by only plotting a point when the crack increased, the distribution did not adhere to this recommendation. There are a number of techniques that are generally used to simplify the data. The two that were used are the Secant and the Incremental seven point Polynomial methods. Post-processing of the results through LabVIEW required the user to identify the same base directory as was the case when the test was running and to enter a few geometrical values for the CT-specimen.

5.2 Post-processing

Post-processing was done through another LabVIEW file called CGMPostProc.vi.

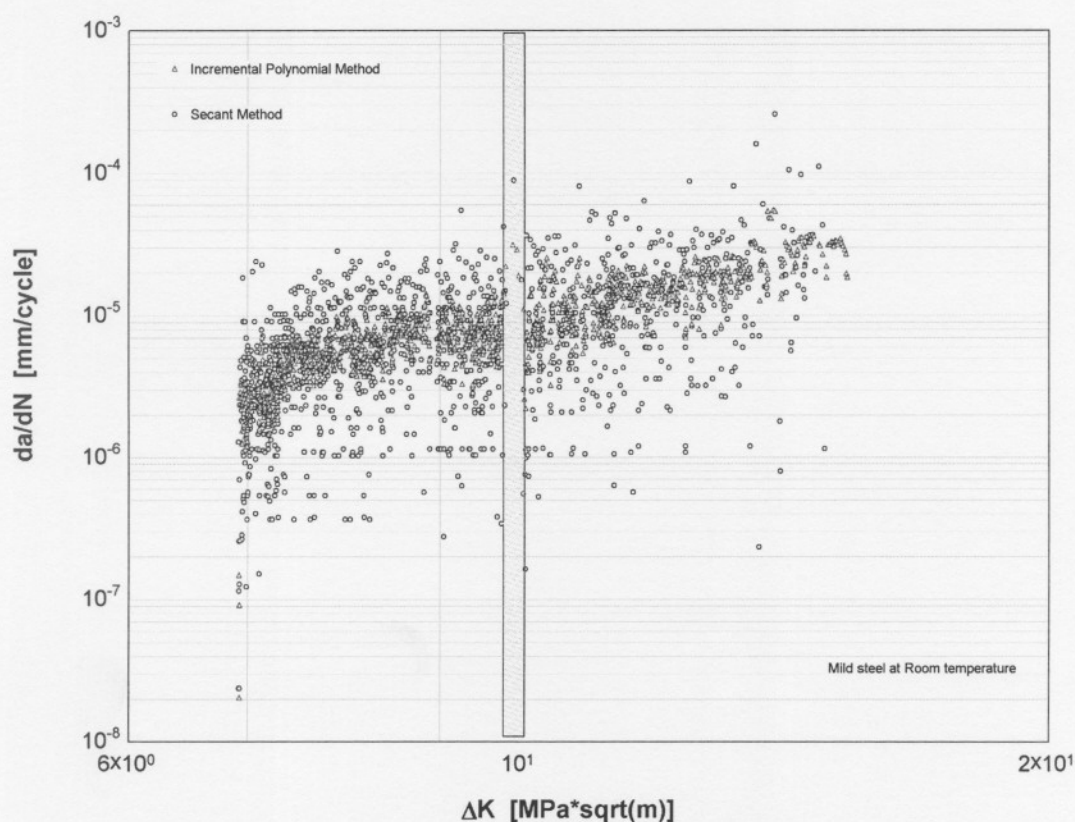


Figure 5-1: Graph of da/dN vs. ΔK with error.

Figure 5-1 shows the processed results for change in crack length per cycle and the change in the stress intensity factor for the plotted range. The vertical block indicates the faulty measurement as indicated by the encircled area in Figure 4-3. It can be observed that the number of points in this block is significantly less than in the surrounding areas. This is due to the sudden increase in the faulty crack length measurement that did not allow for actual values to be plotted until a measurement greater than the faulty one was measured. Fortunately it did not affect the rest of the results negatively. The post-processing program logged the Polynomial method results in finaldatapoly.xls and the Secant results in dadNvsDeltaK.dat. Figure 5-1 shows that the Secant method has a much larger scatter band than the Polynomial method. This is mainly due to the fact that the Polynomial method uses an averaged value to produce the indicated results.

5.3 Discussion of Results

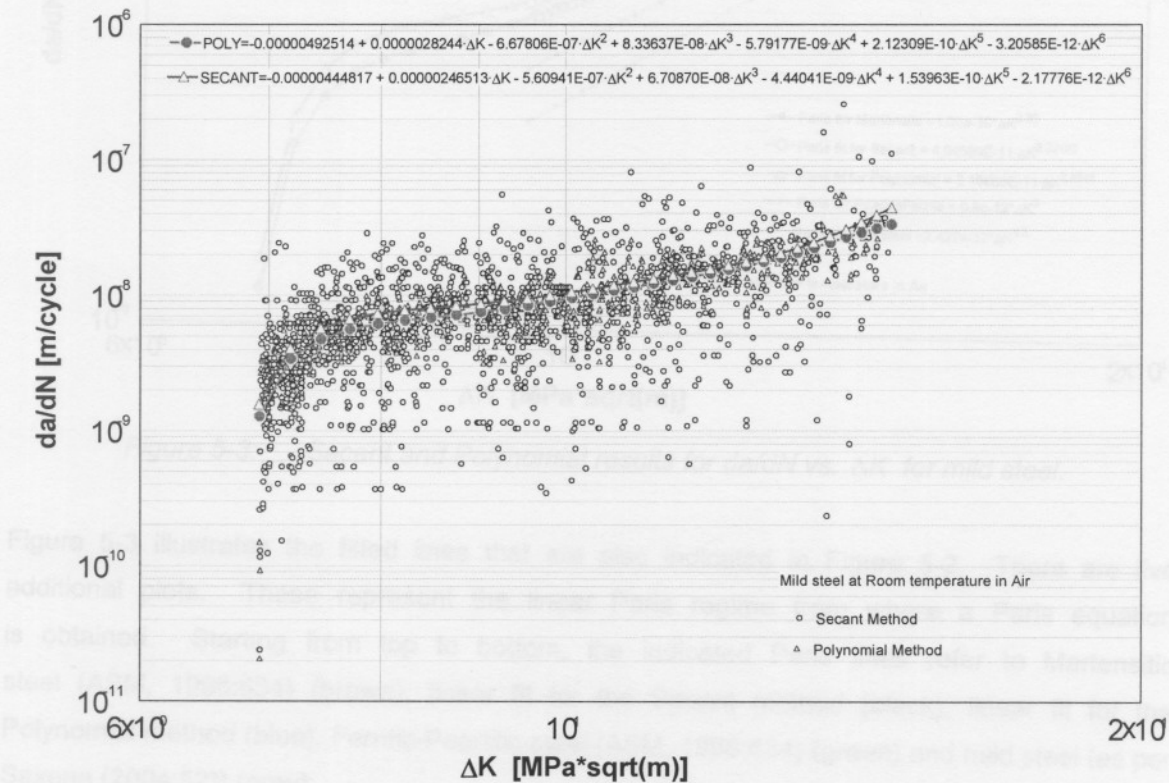


Figure 5-2: Fitted lines for the for da/dN vs. ΔK for the Polynomial and Secant methods.

Figure 5-2 shows the corrected data for the plotted points of the seven point Polynomial and Secant methods. The number of data points for the Secant method and the Polynomial method were 1262 and 1256 respectively. Take note that the dimensions of the crack growth rate were changed to meter per cycle to facilitate ease of use. It furthermore shows the fitted (sixth order

Polynomial) lines (pink and orange) for both these methods. A linear line can be identified by looking carefully at the fitted lines.

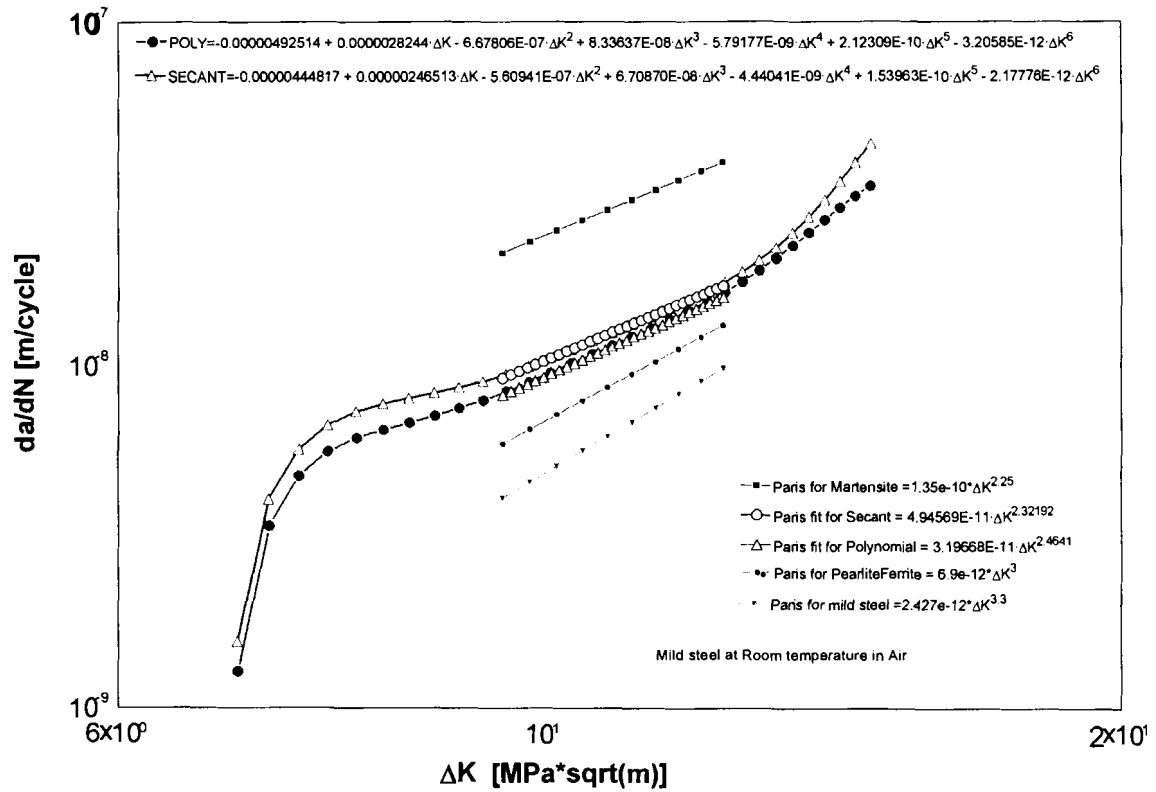


Figure 5-3: Secant and Polynomial results for da/dN vs. ΔK for mild steel.

Figure 5-3 illustrates the fitted lines that are also indicated in Figure 5-2. There are five additional plots. These represent the linear Paris regime from where a Paris equation is obtained. Starting from top to bottom, the indicated Paris lines refer to Martensitic steel (ASM, 1996:634) (brown), linear fit for the Secant method (black), linear fit for the Polynomial method (blue), Ferritic-Pearlitic steel (ASM, 1996:634) (green) and mild steel (as per Saxena (2004:52)) (grey).

It follows that the Paris equation for the Secant and Polynomial method for local mild steel at room temperature respectively were found to be:

$$\frac{da}{dN} = 4.95 \cdot 10^{-11} (\Delta K)^{2.32} \quad (4.1)$$

$$\frac{da}{dN} = 3.20 \cdot 10^{-11} (\Delta K)^{2.46} \quad (4.2)$$

where the dimensions of ΔK is $MPa\sqrt{m}$ and $\frac{da}{dN}$ is in $m/cycle$.

According to ASM (1996:634) the Paris equation is generally valid for ΔK ranging between 9.89 and $57.14 \text{ MPa}\sqrt{\text{m}}$. This holds true for the presented experimental data. The yield strength of the aforementioned mild steel as per Saxena (2004:52) is 230 MPa and that of the tested mild steel (300WA) was 300 MPa. The variation of mild steel grades and composition made it difficult to compare these mild steels directly. The test results for both the Secant and Polynomial methods lay between the Martensitic and the Ferritic-Pearlitic lines from which a reasonable assumption was made that the test results were within the expected unit order. The curves show that the difference between the Polynomial method and the Secant method was relatively small but may warrant further investigation to identify which method was more suitable. More tests of the same material are required to fully validate these results.

5.4 References

ASM. 1996. *Handbook Fatigue and Fracture*, 19. ASM (The Materials Information Society). 1057p.

ASTM E647-00. 2002. *Standard Test Method for Measurement of Fatigue Crack Growth Rates*. 42p.

SAXENA. 2004. Master Curve Approach for Through-thickness Crack Length in Plates with Central Surface Notch. *IE (I) Journal*, 85:49-54, May.

CHAPTER 6 - Conclusion and Discussion

6.1 Conclusion

The first part of this study reviewed the theory and the methods of fatigue crack growth monitoring. Optical techniques were then identified to complete this task. To be more specific, a digital image analysis method that was cost effective was proposed to measure the crack growth rate of a standard CT-specimen, in order to find a Paris equation for the specific material.

The digital image analysis method that was used is a simple and effective method to monitor fatigue crack growth. In order to bring about the method, a systematic approach was followed to design and assemble the test facility. The test facility was made up of a Nikon D70, an Instron 1603 EMR machine and controller, lighting equipment, a PC and some connecting equipment. In addition, Nikon Capture software permitted digital images to be sent directly to the hard drive at pre-determined intervals. Vision Assistant software from National Instruments provided image calibration. A program that was written in LabVIEW was used to measure the crack growth from the digital images and also to acquire the load and frequency data from the Instron 1603.

All the data was logged as it was processed to enable the post-processing (through another LabVIEW program) which in turn provided a valid Paris equation. For the mild steel specimen there was a single technical hitch but it was rectified using the additional images that were stored during the test.

The set-up as illustrated in Figure 3-10 had the following expenses (excluding the available items):

Hardware	R 18 000
Software	<u>R 6 400</u> (R 25 600)
Total	R 24 400

It has to be said that universities receive large discounts from the software companies. The software amount in brackets indicates the commercial price for the same software. Furthermore the LabVIEW base package, which was used to write the main program, was previously acquired and not included in the above costs. A similar set-up can be purchased from Instron at a ten fold amount, depending on the specific requirements.

It can also be concluded that image analysis software was indeed successfully used to find a crack growth equation through an evaluated design methodology. What's more an Operating Manual and a Procedure for Image Calibration was presented in APPENDIX A and APPENDIX B respectively.

6.2 Advantages and Disadvantages of the Method

The disadvantages of the method was its sensitivity to reflection, its smooth specimen surface finish requirement and the fact that the system did not form a unit but operated more like three separate components (the computer, the camera and the Instron 1603).

This method allowed for continual monitoring without stoppages, allowed good referenced data from where problem areas could be investigated and is a relatively cost effective method. Should any irregularities occur with the data, it is possible to trace the source of this problem easily as the images record the exact event. Most other methods only allow for the results to be examined if anything irregular occurred.

6.3 Recommendations

The system can further be improved on. For instance, once the cost of a high resolution CCD video camera comes down, the current camera can be replaced. It will allow for even more accurate measuring and could support control by the software to capture an image at a predetermined time and at faster time intervals.

To eliminate the changes to the program settings for every sample, the contrast of the crack in the specimen could be improved upon. This should reduce the sensitivity that the surface of the specimen has shown.

Another important aspect in fatigue crack growth testing is the testing machine and the control thereof. When a variable load is applied, a predetermined load history is often used to find the specific crack growth rate. In the case of the mild steel specimen, the Instron 1603 has proven that the magnet air gap may become a problem. It is therefore suggested that the test machine could use a better control system or that the limitations of the machine could be better defined.

The design that was presented has stopped short of the detailed design step of a systematic approach to design as numerous tests are still required to fully validate the operation. The

manner in which crack growth is monitored allows for the possibility to apply this method to alternative materials such as composites or ceramics.

APPENDIX A - Operating Manual

A.1 Introduction

This operating manual intends to give the user a clear indication of the operating procedures as well as the requirements, with special focus on image calibration provided in APPENDIX B - Procedure for Image Calibration. The software is used with certain equipment (see A.3) and the continuous use of this equipment is advised. Any change to the set-up, may lead to undesirable results. The operating manual should be used in conjunction with the Instron 1603 operating manual. Furthermore, the specimen preparation forms a critical part of the process. A smooth surface finish of 1µm or less is required.

A.2 Program Functionality

The program uses images from the camera to measure the opening of the notch of the CT – specimen, but also to measure the crack length as the image is received. At the same time, the data from the Instron 1603 EMR-machine is stored in a .lvm-file (LabVIEW measurement file). Up to now, the program has been used to find the crack growth rate (FCGR) in fatigue testing for constant amplitude load. It may be used for other applications, besides FCGR, where crack length is a required parameter within the capacity of the testing machine. Other possible test methods that may utilise this set-up include creep and fracture toughness testing.

A.3 Equipment

The equipment includes an Instron 1603 Electromagnetic Resonance machine (EMR) which is used to apply constant amplitude load to the Compact Tension (CT) specimen. The Instron-machine uses a controller to specify the load parameters and provides output to a National Instrument connector block to send data to the PC via a NI 6023 PCI-card. The specimen is of the notched type and the test follows the ASTM E647 (2002) standard. Once the fatigue experiment starts, the camera takes photographs of the CT-specimen at certain time intervals (approximately every eight seconds). The digital images and the data from the Instron machine are simultaneously sent to the PC. The lighting is provided by fibre optic lights and it is rigidly set-up to avoid being influenced by the vibration of the Instron-machine. Furthermore, the lighting on the specimen is kept consistent even though relatively small amounts of movement occur. The equipment is presented in Figure A 1.

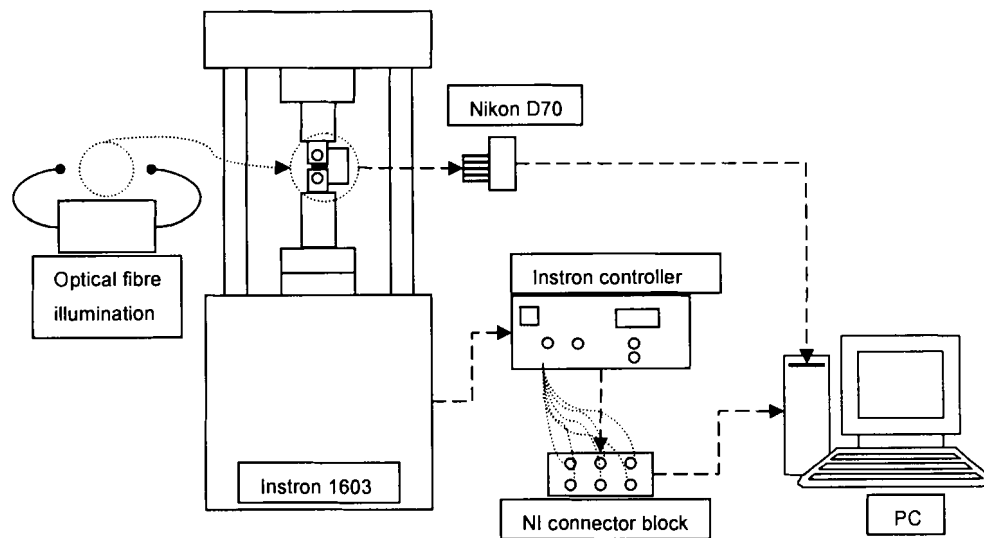


Figure A 1: Illustration of the equipment.

Take note that the program is highly dependent on the lighting, as specific areas require illumination and any shadow should be avoided.

A.4 Program Requirements

The program is called CGM.vi which is short for Crack Growth Monitoring. It is written in LabVIEW 7 and requires the installation thereof. Furthermore, the calibration procedure (APPENDIX B) requires the installation of NI Vision Assistant. Images are required and they are captured through Nikon Capture 4 which allows for time lapse photography of the Nikon D70. The data files are .lvm (LabVIEW measurement), .xls (Microsoft® Excel™) and .dat (data) files. They can be viewed by the majority of word processing or spreadsheet applications.

The directory which is selected as base directory should include the files mentioned in the calibration procedure. Figure A 2 illustrates the base directory and among other, the inclusion of the images from the camera. The camera software should be set-up to save the images in the base directory as well. Also, the camera and software should then be set-up to start immediately after the program has commenced.

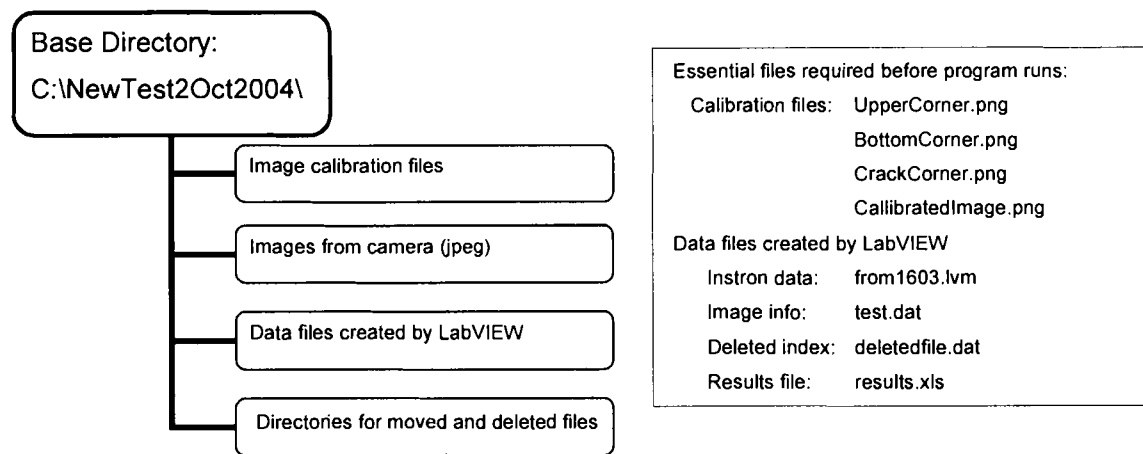


Figure A 2: Base directory - content, allocation and essential files.

A.5 Program Use

Initialise the LabVIEW file called CGM.vi. To run the program, press the arrow () located on the menu bar of LabVIEW. The screen will become inactive for editing and only the green button (located in the bottom right-hand corner) will enable the programme to continue. Next, the user is required to identify the base directory and a number of calibration files (as indicated in Figure A 2 and in APPENDIX B - Procedure for Image Calibration). Additional information on specimen preparation is also presented here. The image constant value should then also be added.

After this, the tab changes from an image information panel to an output actual results page. Here, the different output signals from the Instron 1603 can be visually monitored together with the results of the image measurements. If the test requires stopping, the program can be paused () on the LabVIEW menu bar and restarted by pressing the same button. During this time, however, no data will be saved and the logged data from the Instron machine will not show pausing but will continue to log where it left off.

There are two indicators: The first shows the user when the data from the Instron 1603 is saved to file and the second indicates if the program is waiting for an image file from the camera. The delay which is indicated by a waiting time indicator normally displays an eight or nine second wait, which serves as an indicator if the images are not received by the program. It is then advised to pause the program, stop the machine, and look at the camera and the Capture 4 software. Make a note of the time delay as the program uses the time properties of each image to create a_{crack} vs. time data. Pausing then causes a time delay which has to be corrected

before post-processing starts. An additional beep function has been added to beep once for every second after 100 seconds have elapsed without a picture having been taken.

A.6 Data Acquisition

The saved data, as previously mentioned, is located in the base directory. The data from the Instron machine is saved in *from1603.lvm*. This file contains the time during which the acquisition starts and stops, at intervals of 0.1 s. At each interval, a value for the frequency, the mean load, the maximum load, and the minimum load is recorded. The *test.dat* file contains a numbered image file list, the date and the time it was taken, the crack length value, and the crack mouth opening displacement value. The program creates two folders in the base directory: *deletedfiles* and *movedfiles*. The image files are subjected to measurements made by the program. If the previously measured value for the crack length is smaller than the current value, the image is moved to the *movedfiles* directory, otherwise it is deleted. The *movedfiles* directory contains a results file called *results.xls*. This file contains the number of the image, the time in seconds from start, the crack length, and the CMOD.

A.7 Post-processing

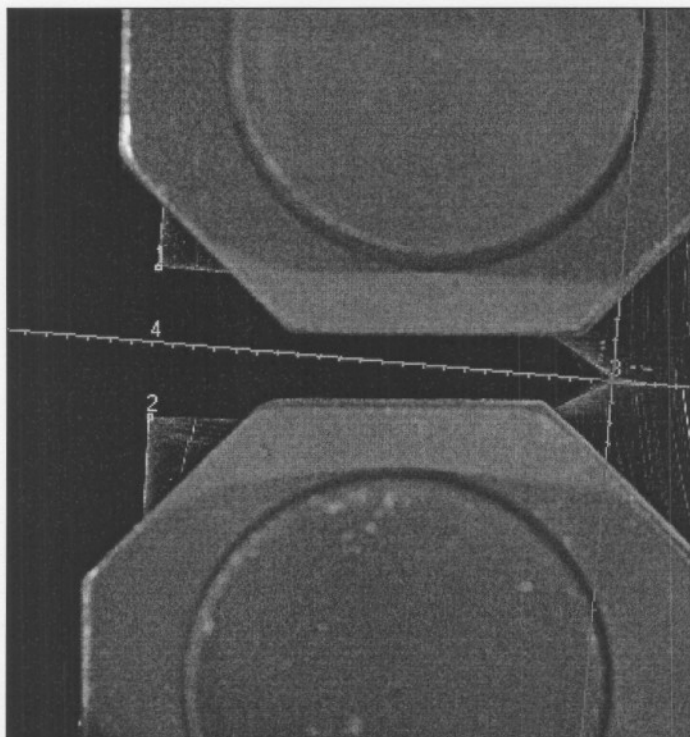
Once again LabVIEW is used. This time though, it is used to evaluate the data saved once the test has ended. The file used is called *CGMPostProc.vi*. It uses the data in the aforementioned *results.xls* and *from1603.lvm* files. The user is required to establish the maximum and minimum force, and the frequency for the test from the *from1603.xls* file. Apart from these parameters, the geometry measurements are also required inputs. When all the inputs are made (take care to enter the values in the indicated units) the data is processed in the Secant and Polynomial methods to provide da/dN vs. ΔK -data for the specific material.

A.8 References

National Instruments. 2003. *IMAQ Vision Concepts Manual*. p.3-1 - 4-8.

APPENDIX B - Procedure for Image Calibration

For use with: Nikon D70
 Instron 1603
 LabVIEW 7
 NI Vision Assistant Version 7.0.0



Use with Calibration.scr
Outputs used by CGM.vi

B.1 Requirements

- National Instruments Vision Assistant (installed program);
- “Captured image” (saved on the hard drive of the PC) of mounted CT-specimen with lighting as per test;
- File: Calibration.scr (Vision Assistant file); and
- Crack Mouth Opening Displacement (CMOD) measured value of corner to corner (see pattern matching 1 and 2 as indicated by Figure B 3).

B.2 Opening

Initialise Vision assistant:

Click on file → Open script → select: Calibration.scr.

Click on file → Open image → select: “the Captured image”.

The discussion that follows, follows the order of operation in the Calibration.scr file exactly.

- ☛ Take note that the operations are dependent on the preceding operation, which means each operation should be finished before continuing with the next.

B.3 Subtract Constant

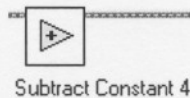


Figure B 1: Subtract constant icon.

The subtract constant operation aims to minimise the noise or small speckles on the surface of the image. Before this value is entered, a histogram of the crack growth area is investigated. The histogram function is located at the top of the image processing functions. Figure B 2 shows the histogram for the selected area. A good subtract constant value that is suggested for use, is the sum of the mean and the standard deviation values. For this specific image the value corresponds to 41.69. Double-clicking on the subtract constant icon (Figure B 1) then allows this value to be entered.

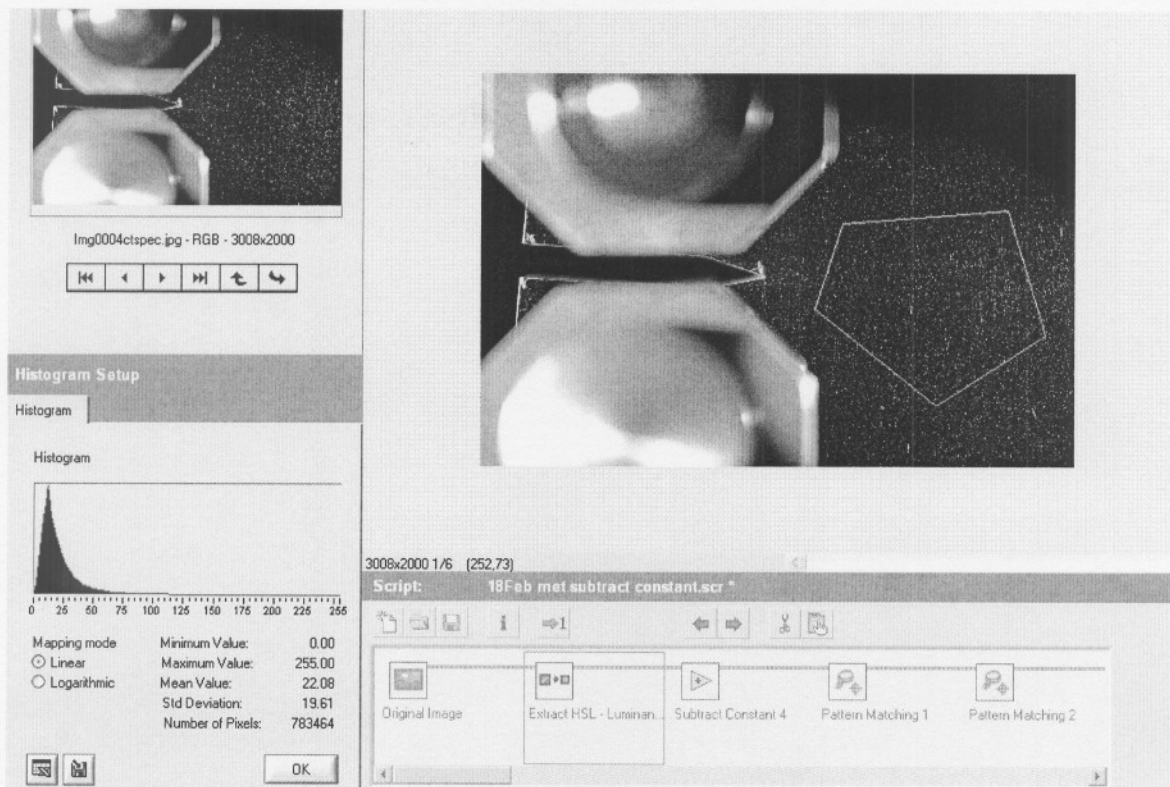


Figure B 2: Histogram operation.

B.4 Pattern Matching Set-up

It is important to work very accurate when selecting the different images, rectangle selection size, and positioning as it will be used during the calibration and actual measurements. Any error may result in faulty values. Once this step for pattern matching 1, 2 and 3 is finished, the image should be similar to the following in Figure B 3:

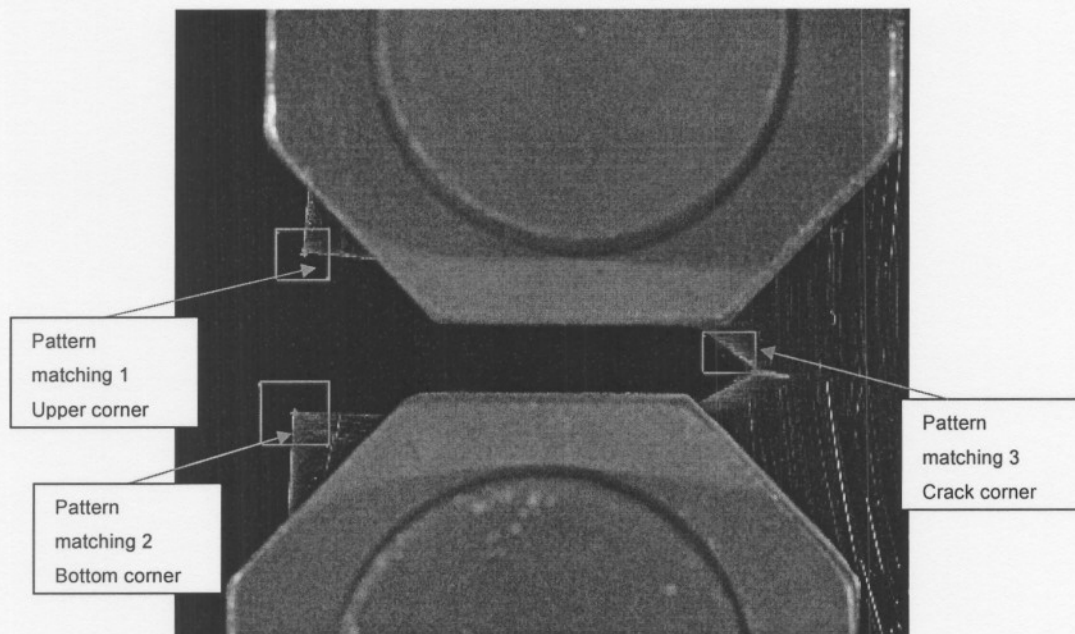


Figure B 3: Image with indicated pattern matching selections.

B.4.1 Pattern Matching 1

- Double-click on the pattern matching 1 icon as indicated in Figure B 4;

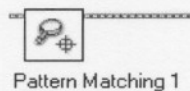


Figure B 4: Pattern matching 1 icon.

- Choose create template;
- A new window appears with the current image;
- Scroll down to the upper corner of the CT-specimen opening (as illustrated in Figure B 5);
 - ✳ When zooming, hold shift to zoom out;
- Zoom so that only the upper corner is visible in the window (Figure B 5);
- Choose the rectangle selection tool and draw a rectangle which only includes the upper corner of the specimen;
- The size of this rectangle should be: 111 (W) x 84 (H) pixels;
 - ✳ Be careful not to select a part of the upper grip within the rectangle;

- Align the centre of the rectangle to the corner where the edges of the specimen meet (Figure B 5);
- Once you are satisfied that the image looks similar to that of Figure B 5, click OK;
- Save this image in a new directory and remember this location (as you will be required to identify its location later on);
- ✦ A good idea is to save it to a directory named the day of test and reference the file name to the upper corner i.e.:

C:\NewtestDate\UpperCorner.png; and

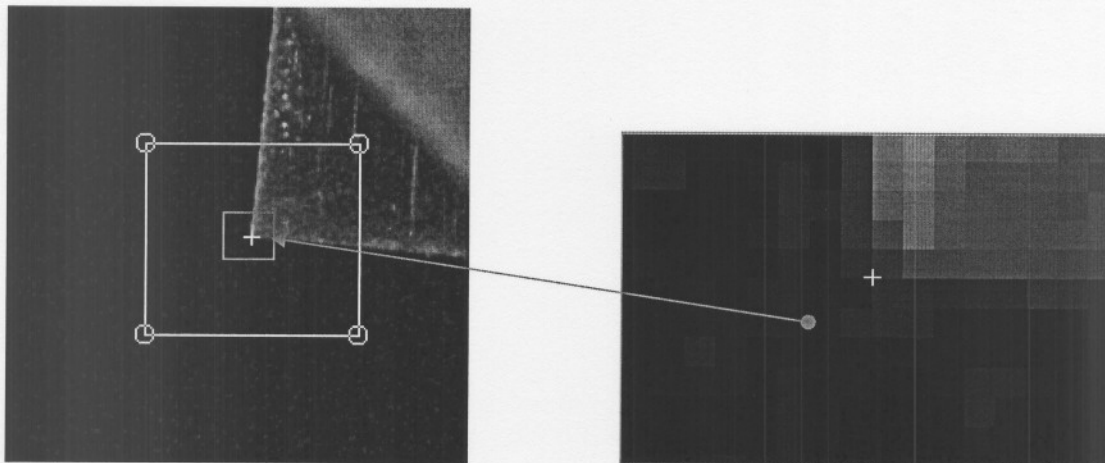


Figure B 5: Upper corner of CMOD opening and Centre alignment with corner.

- Press OK to continue. Point 1 is now identified.

B.4.2 Pattern Matching 2

Repeat the process (as in B.4.1) for the pattern matching 2 icon, and replace the following:

- The rectangle size is: 111(W) x 84(H) pixels;
- Save the image under the same directory i.e.
C:\NewtestDate\BottomCorner.png; and
- Press OK to continue. Point 2 is now identified.

B.4.3 Pattern Matching 3

A similar procedure is used for the crack corner pattern matching, as in Pattern Matching 1; however, it is of utmost importance to specify this selection while excluding the grips. This selection indicates the reference point from where all measurements will be made.

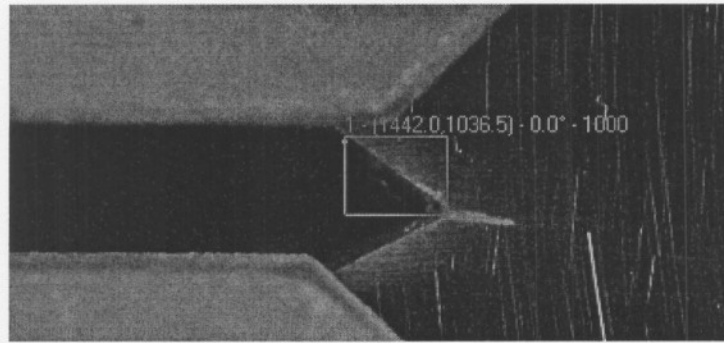


Figure B 6: Area selection for reference point location.

Figure B 6 indicates the position for the selection of an area from where the crack will be measured. Take note that the bottom right-hand corner of the red rectangle indicates the reference point. It is located at the point where the crack is most likely to initiate, and this point is highly reliant on user input. The user should therefore be as accurate as possible when zooming and selecting.

When identifying the crack corner pattern, allow the pattern to contain the whole open area. In other words, leave the corner edge just out of picture. This will allow the measure procedure to find an initial crack length in the region of 0.1 mm. The first measurement is then taken to be this value and is later used as the term, $a_{correct}$, which is added to the crack length measurement to find the true value. This value should then be **negative** for most cases with regards to the location from where the measurements of a and a_n are made (see ASTM E647, 2002:11). The value for a is then determined by using the following equations:

$$a_{n1} = a_{correct} + a_n \quad (B.1)$$

and then

$$a = a_{crack} + a_{n1} \quad (B.2)$$

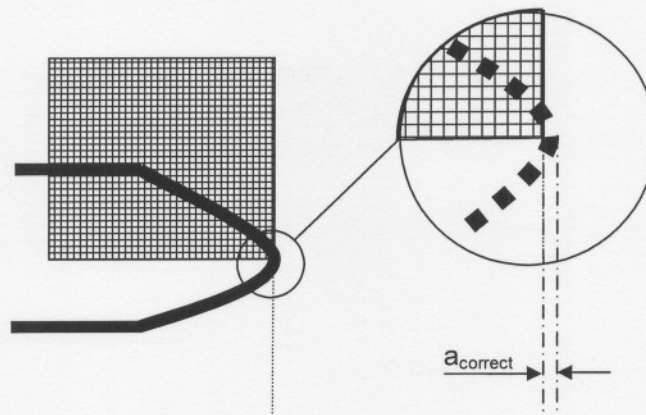


Figure B 7: Crack corner pattern selection note.

Repeat the process (as in B.4.1) the pattern matching 3 icon, and replace the following:

- The rectangle size is: 111(W) x 84(H) pixels (keep this size exactly);
- Save the image under the same directory i.e.:

C:\NewtestDate\CrackCorner.png;

Once saved, you will return to the pattern matching set-up, template tab (Figure B 8);

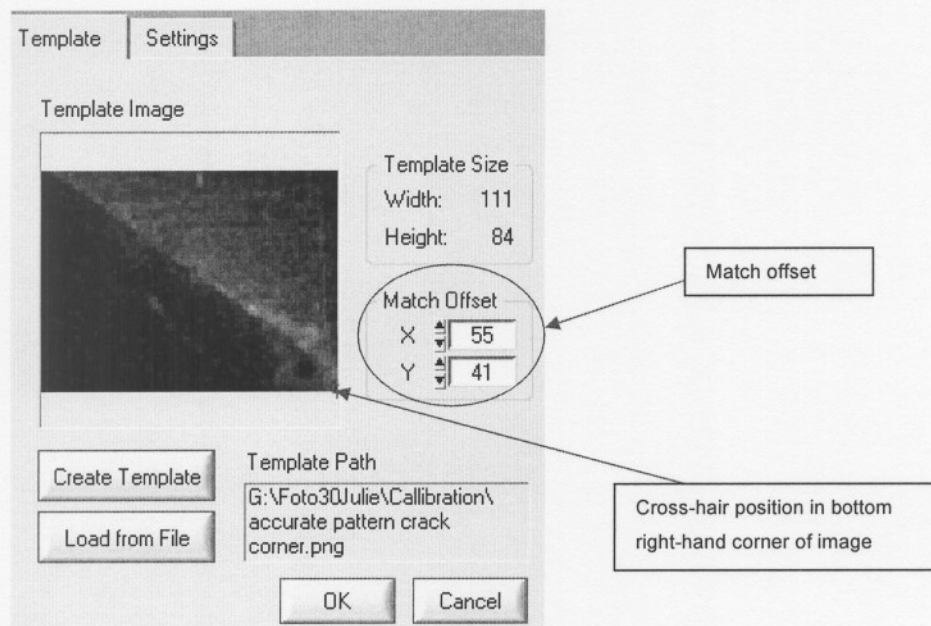


Figure B 8: Pattern matching set-up, template tab.

- The match offset (x and y) parameters indicate where the cross-hair position is. Keeping in mind that this point indicates the start position of the crack, it should be moved to the

bottom right-hand corner. You may enter large values (eg. 100) to both the x- and y-parameters and the Vision Assistant will accordingly limit the values to the pattern image size. The indicated values of Figure B 8 should match your values; and

- Press OK when finished. Point 3 is now identified.

B.4.3.1 Calliper 1

This calliper measures the distance between the pattern matching points 1 and 2 and creates a mid-point between them.

- Double-click the calliper icon to view.
- No adjustments/settings are required.
- Press OK to continue. Point 4 is now identified.

B.4.3.2 Calliper 2

This calliper measures the angle from the horizontal plane to the line formed between points 3 and 4.

- Double-click the icon to view. See Figure B 9.
- No adjustments/settings required.

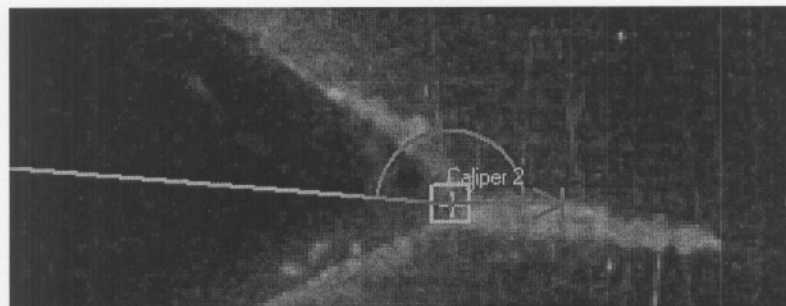


Figure B 9: Calliper 2 - Angle measured from horizontal to the line connecting points 3 and 4.

B.4.3.3 Calibrate Image 1

- Double-click the calibrate image 1 icon, choose edit calibration. A picture of the current image can now be seen.
- Step 1 of 3: Select the camera pixel type. Zoom out to have the full image visible. Choose square pixel type. Choose next.
- Step 2 of 3: Specify the pixel ratio. Select the camera pixel type Choose Point 1 (1-Pattern matching 1 – Match 1) and Point 2 (2-Pattern matching 1 – Match 1) when selecting the required two points. The real measurement between these two points

should have been measured previously (eg. 4 mm) and now entered into the open box. Choose the units in millimetres when entering the value. Click on next.

- Step 3 of 3: Specify the calibration axis. The axis origin: choose the existing point option and choose Point 3 (3-Pattern matching 1 – Match 1). The X-axis angle: choose the existing angle option. Choose Point 4 (4 - Caliper 2) and add 180 degrees.
- Choose OK to exit the edit calibration tab. Choose OK again to exit the calibrate image set-up. The image calibration is now completed but the image should still be saved.
- Click on file on the menu bar and choose save image. Ensure that the checkbox for “save image calibration” is checked. Save the .png-file in the same directory as the pattern matching

i.e.: C:\NewtestDate\CalibratedImage.png

Figure B 10 indicates the numbered points and the axis definition.

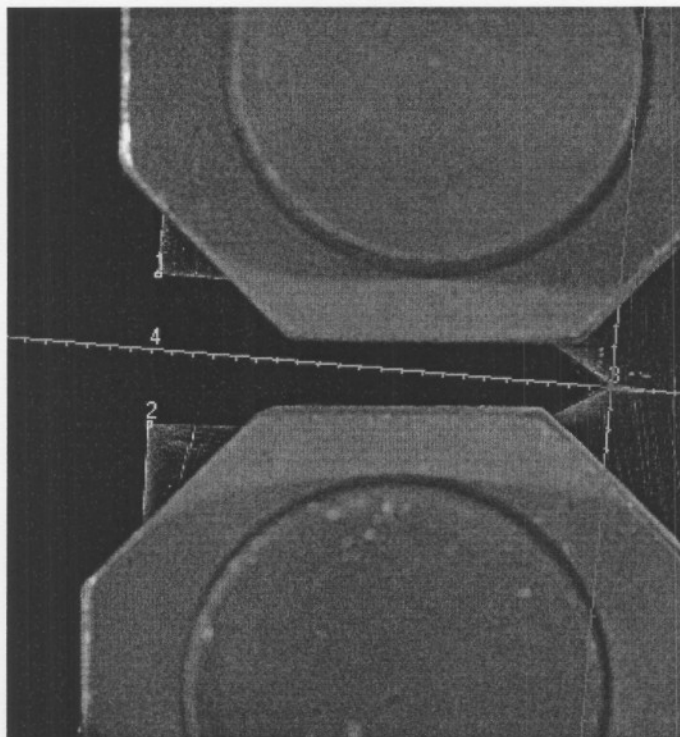


Figure B 10: Calibrated image with numbered points and axis definition.

The image calibration is now complete. To test the image, it is advised to first run the CheckImage.scr file.

APPENDIX C - LabVIEW Programs

C.1 The Sub-vi (CTSpecImage.vi)



Template File Path (upper corner of opening)

C:\Test10Feb\UpperCorner.png



Template File Path 2 (bottom corner of opening)

C:\Test10Feb\BottomCorner.png



Template File Path 3

C:\Test10Feb\CrackCorner.png



File Path (Previously Calibrated Image)

C:\Test10Feb\CalibratedImage.png



CTSpecimenImageSubvi.vi for use in CGM.vi

File Path

C:\Test\movedfiles2\Img1991ctspec.jpg



Crack Length
(Calibrated Results 4)

10.22

Clamp horiz Distance

8.00

CMOD
Crack mouth opening displacement
(Calibrated Results 3)

5.33

default angle of caliper

360

Angle Calibrated Results 2

356.37

last angle of caliper

45.9223

.not. x?

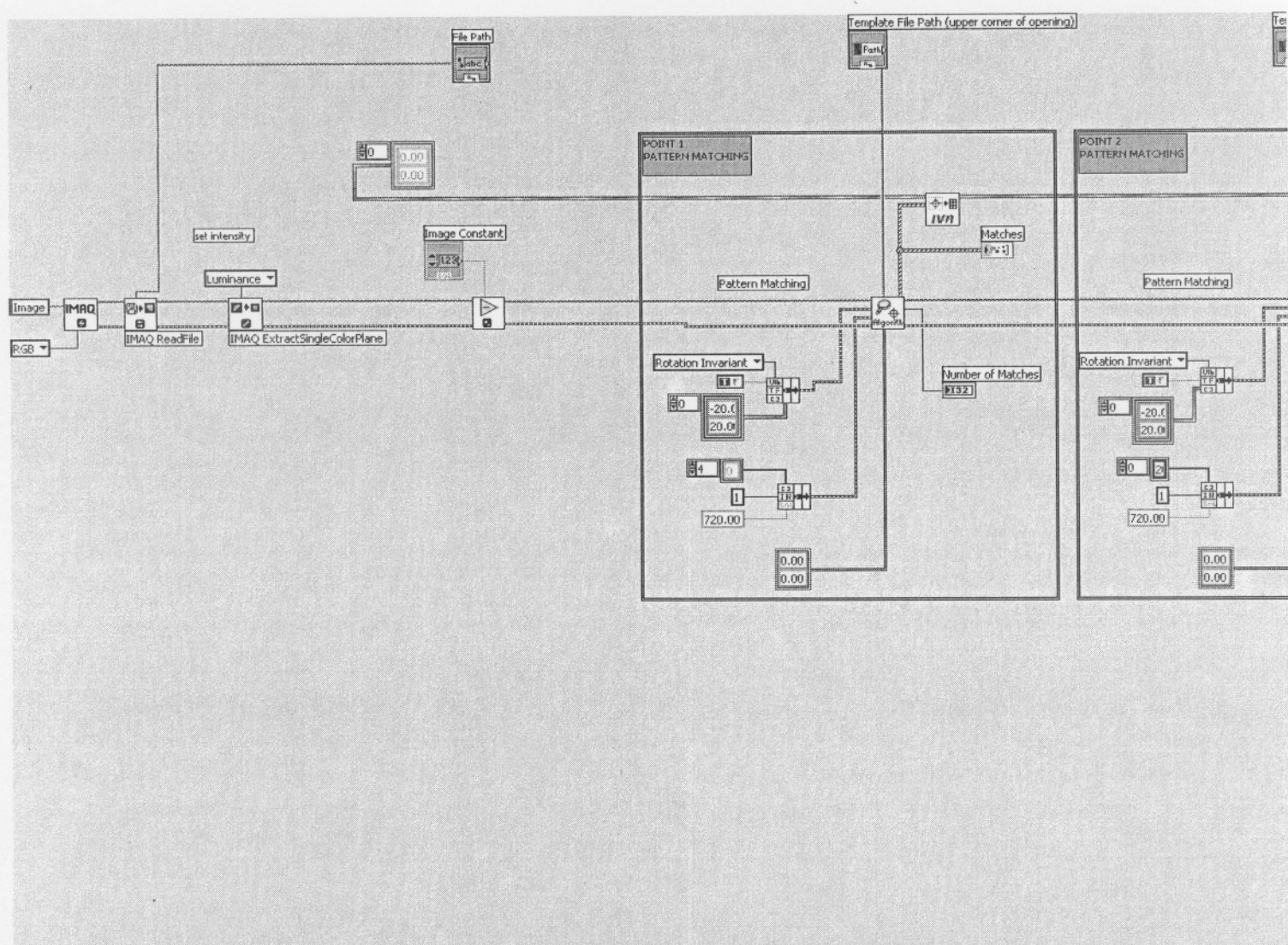


**THIS SUB-VI IS USED to
DETERMINE THE CRACK
GROWTH LENGTH
OF A CT SPECIMEN AND ALSO
THE CTOD (CRACK TIP OPENING
DISPLACEMENT)**

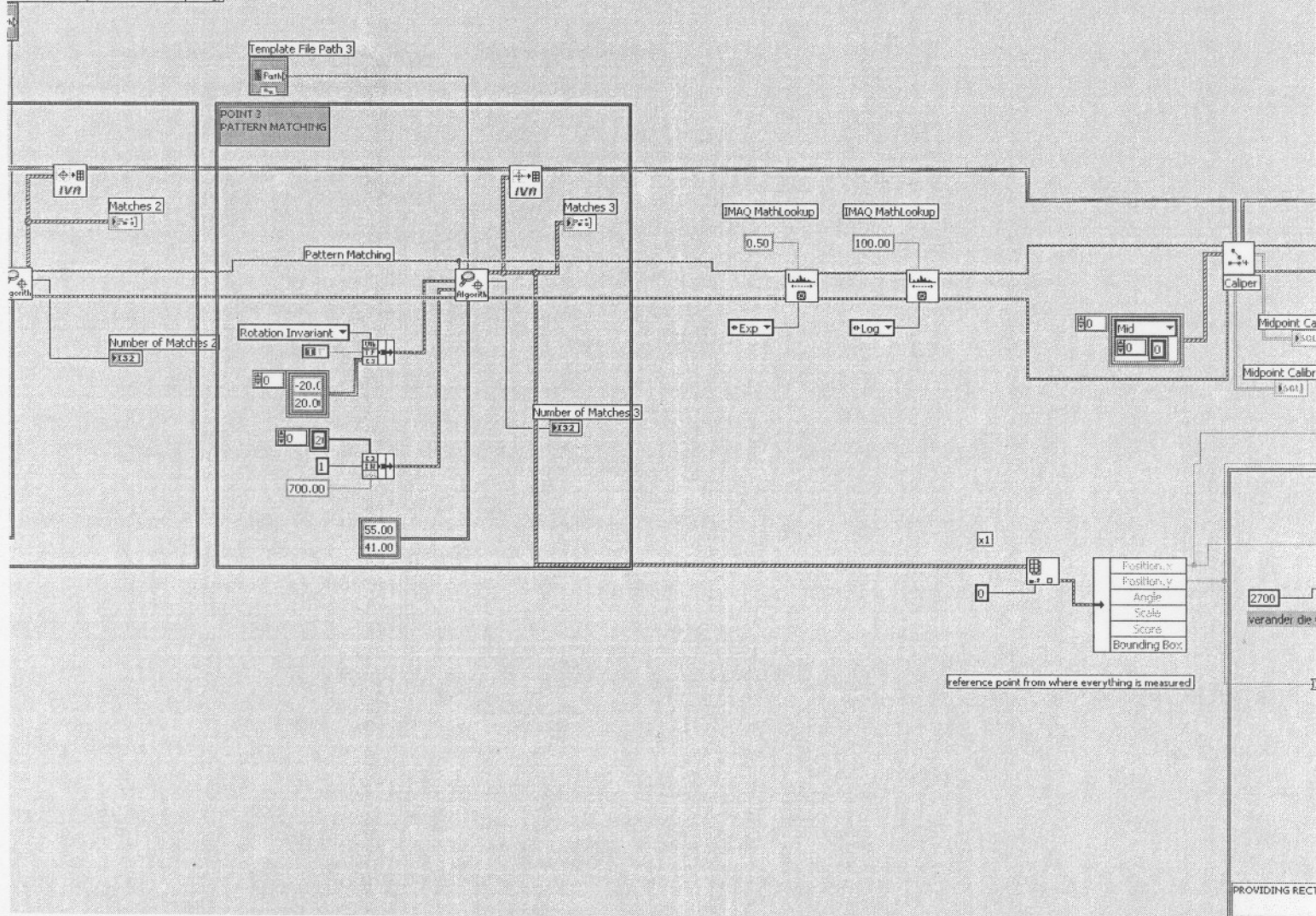
USE IT AS A SUBVI; THE INPUTS
REQUIRED ARE:

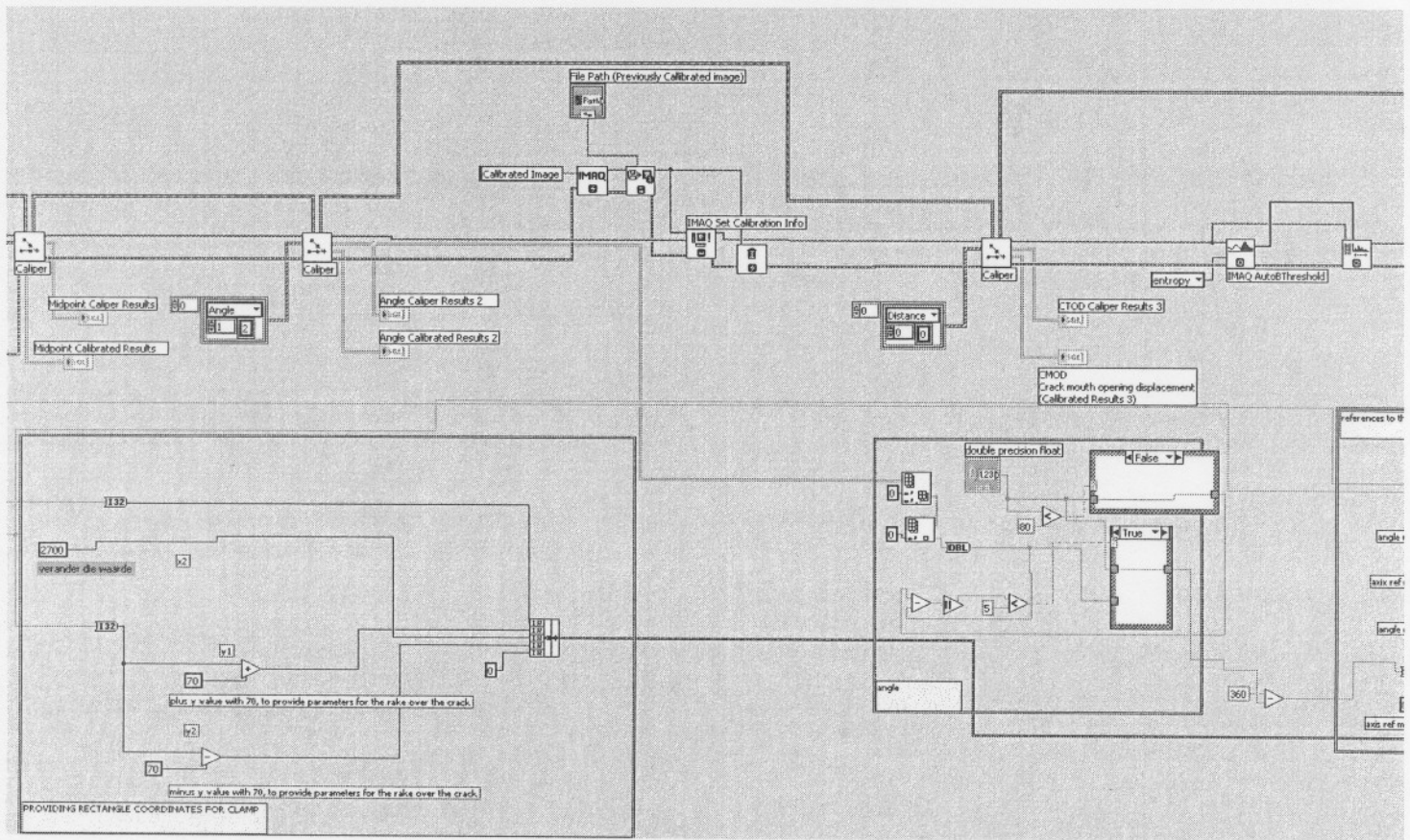
1. THE LOCATION OF THE IMAGE
FILE TO BE MEASURED (TYPE:
6MPIXEL, JPG)
2. THE UPPER CORNER OF THE CT
SPECIMEN OPENING (TYPE: PNG)
3. THE BOTTOM CORNER OF THE CT
SPECIMEN OPENING (TYPE: PNG)
4. THE CALIBRATED IMAGE FILE
(TYPE: PNG)

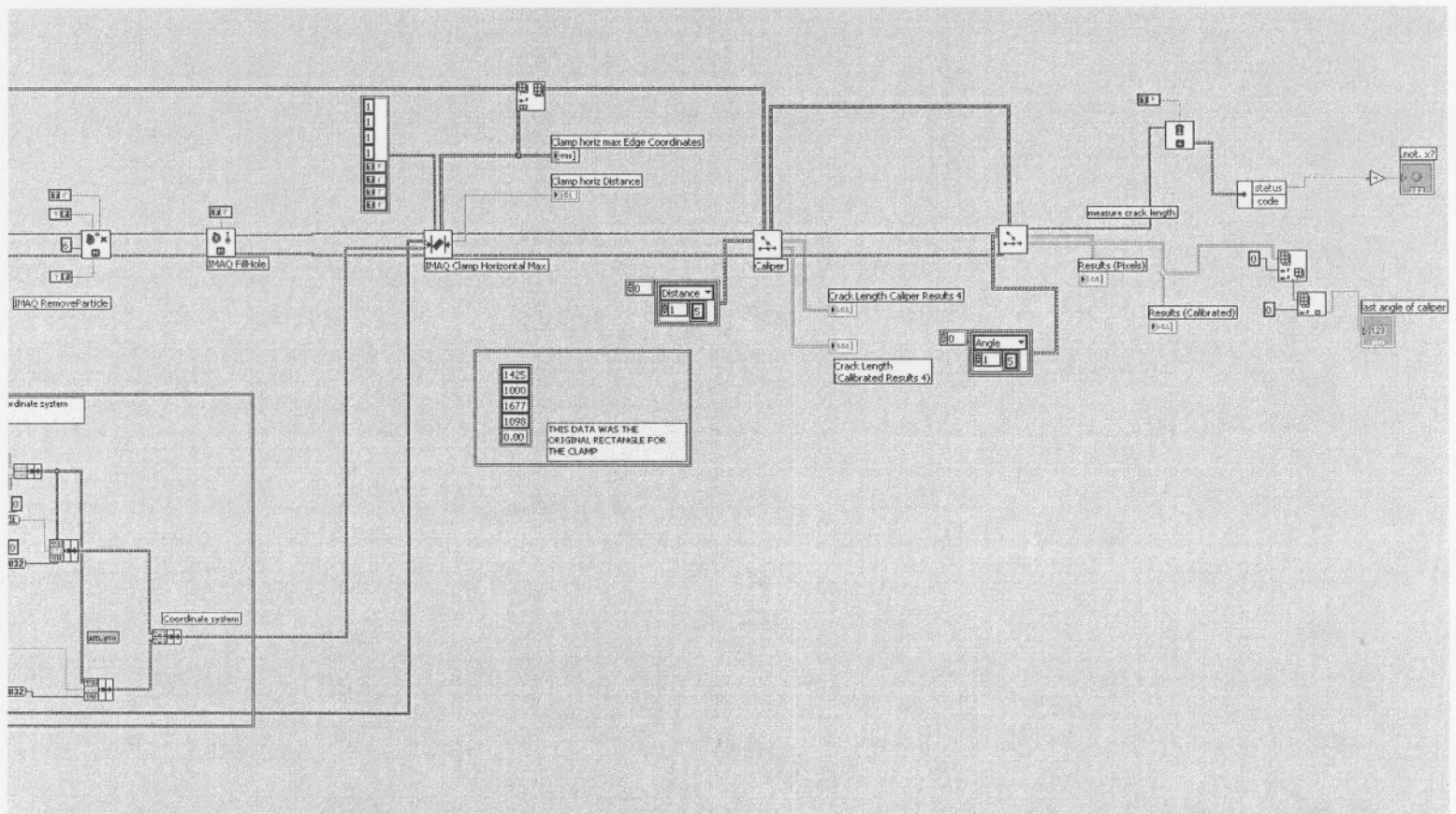
Ensure that the crack length
provides a measurement even
though a crack has not formed yet.
Make a note of this measurement as
it will be used to find the final crack
length.



late File Path 2 (bottom corner of opening)







C.2 The Main Program (CGM.vi)



Before running this program:

From Instron 1603

Before running this program, It is essential to run the following programs:
NI Vision Assistant - Calibration.scr
- CheckImage.scr

Also follow the instructions and the calibration manuals.

Take note that the direction in which the specimen is placed in the grips should face the same direction as the illustrated images.

This program will show an error when a new directory already exists. This is to ensure previous data isn't overwritten.

This tab illustrates the required images that are used to enable image measurements.

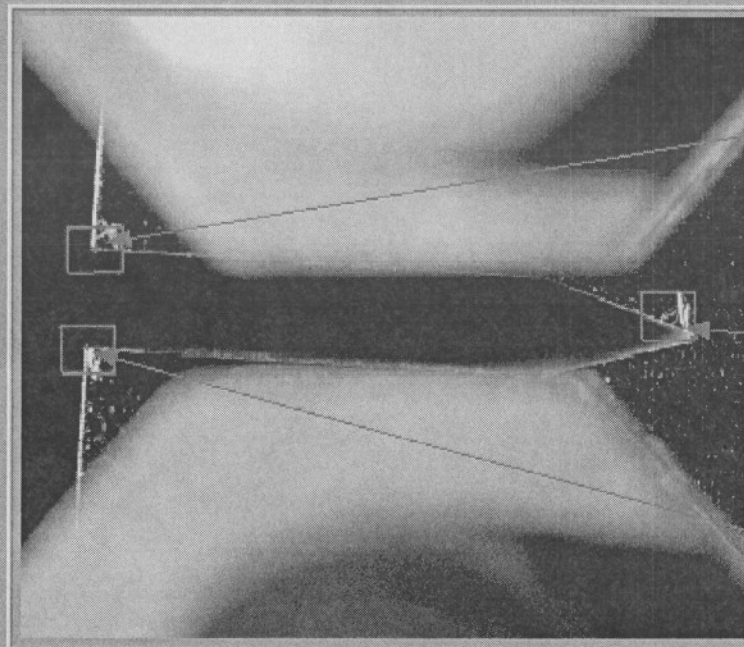
This program uses the specimen as per ASTM E647. Use this standard as much as possible. (Other possible use in creep and fracture toughness testing, with CT specimens - STILL TO BE TESTED)

After running the CheckImage.scr (Vision Assistant file), the Image constant value should be entered here. (Default 0)

Image Constant
0.00

PRESS the GREEN BUTTON TO CONTINUE (Located in the lower right hand corner of the "Before running this program:" tab)

Specimen preparation: surface finish 1 micron. (Ensure no dust particles on specimen surface!)



Template File Path (upper corner of opening)

C:\Test\
UpperCorner.png



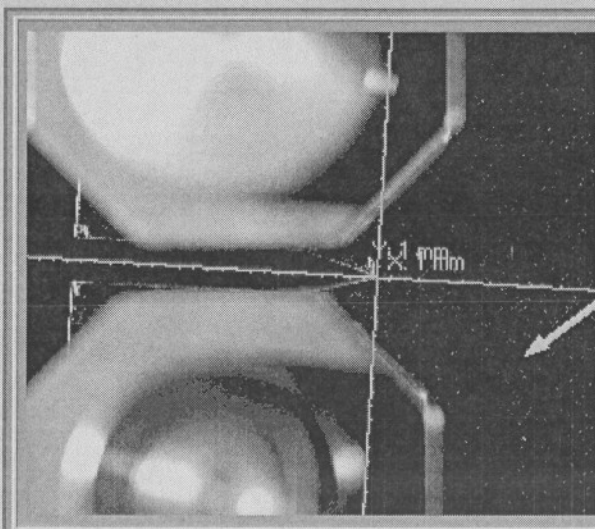
Template File Path 3 (Crack begin possie)

C:\Test\
CrackCorner.png



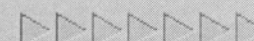
Template File Path 2 (bottom corner of opening)

C:\Test\
BottomCorner.png



File Path (Previously Calibrated image)

C:\Test\
CalibratedImage.png



Press this button to continue

Before running this program: From Instron 1603

The output files are as follow:
from1603.lvm (Data from the Instron 1603)
test.dat (Data from all images
results.xls (Measured data that show an increase in
crack length. Located in the moved directory of the
base directory)



Hold stop until everything stops!!
PRESS THIS BUTTON TO STOP PROCESS



Saving Data (from Instron 1603)



Waiting for picture

0

Elapsed Time (s)

00:00:00.000 PM
YYYY/MM/DD

Starting time

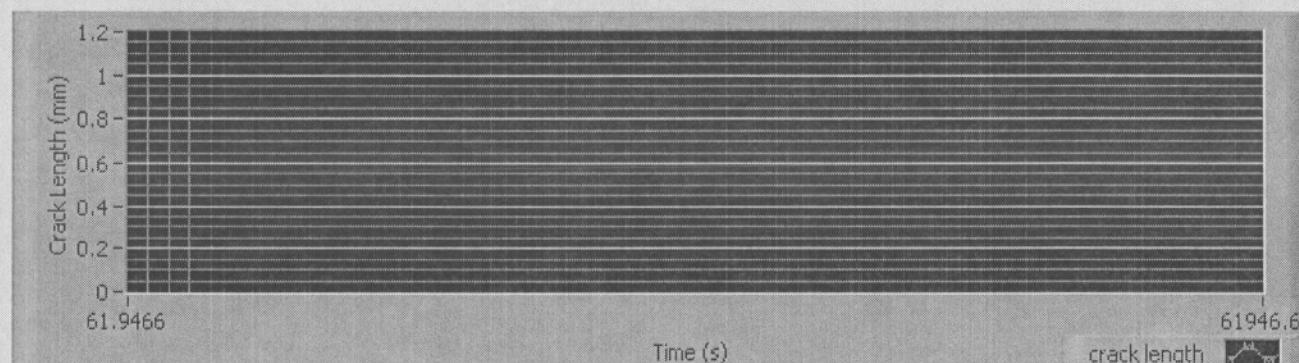
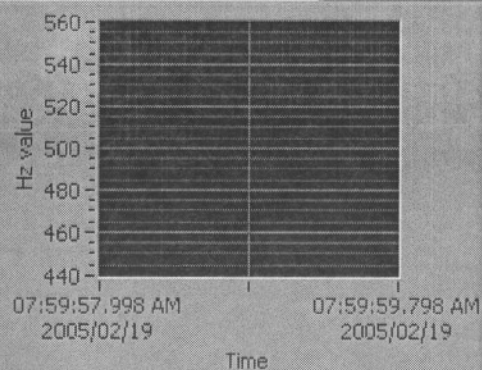
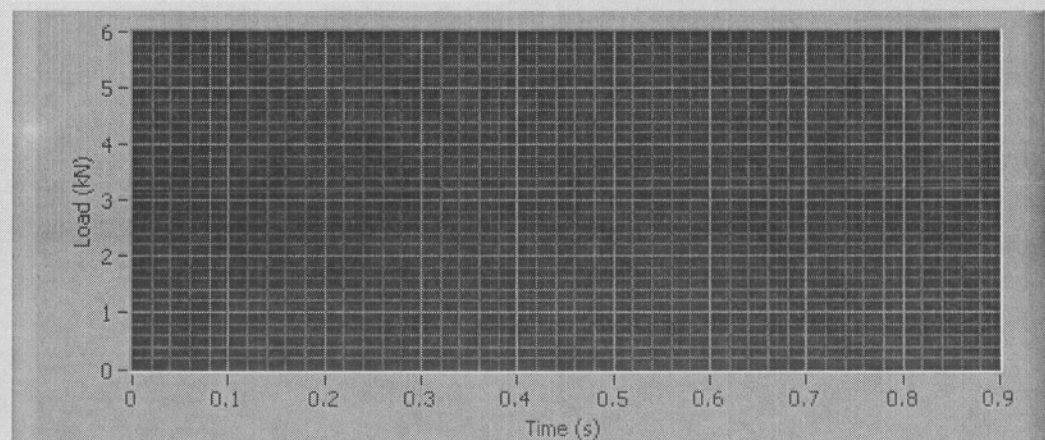


Table of: number of image, time, crack length and CMOD data, for increasing crack length (results.xls)

[illegible]

Data from all images (test.dat)



Dynamic

Mean Load

Maximum load

Minimum load

Sequence 1A

Initial Tab control

Before running this program:

Tab Control

Image Constant

123

Press this button to continue

1

TF

Sequence 1B

New Directories and initial requirements

check directory size

B:\Test

Select Base Directory...

existing dir

C:\Test

FILE

FILE

size

123

TF

STOP

Initialisation Code...

Important:
Check these
before
continuing

CONTINUE

error out

Enable

Yes, bnc cables cl

Yes, warmup over

error in (no error)

Yes, digital camer

STOP

Sequence 2

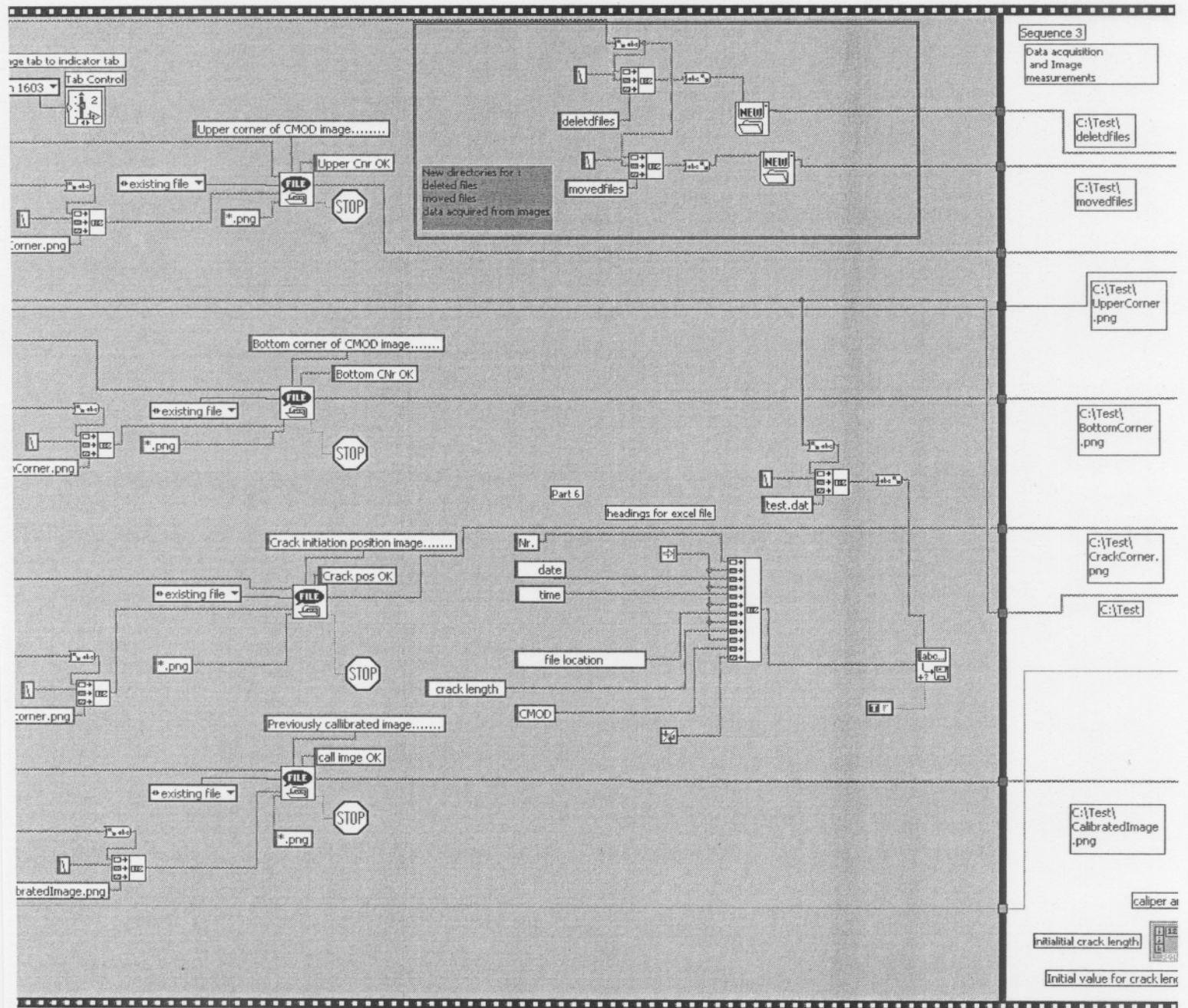
From

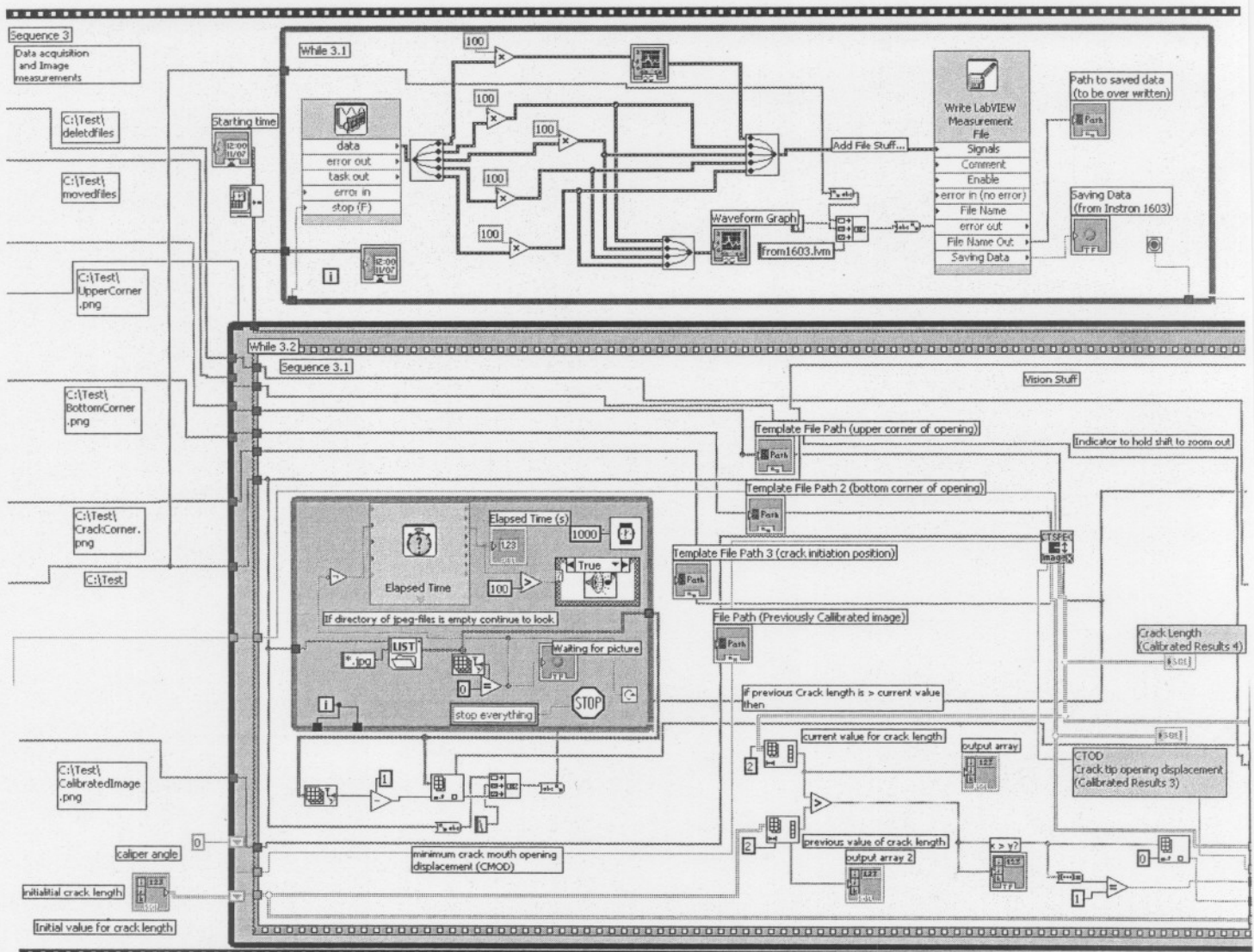
Part 1

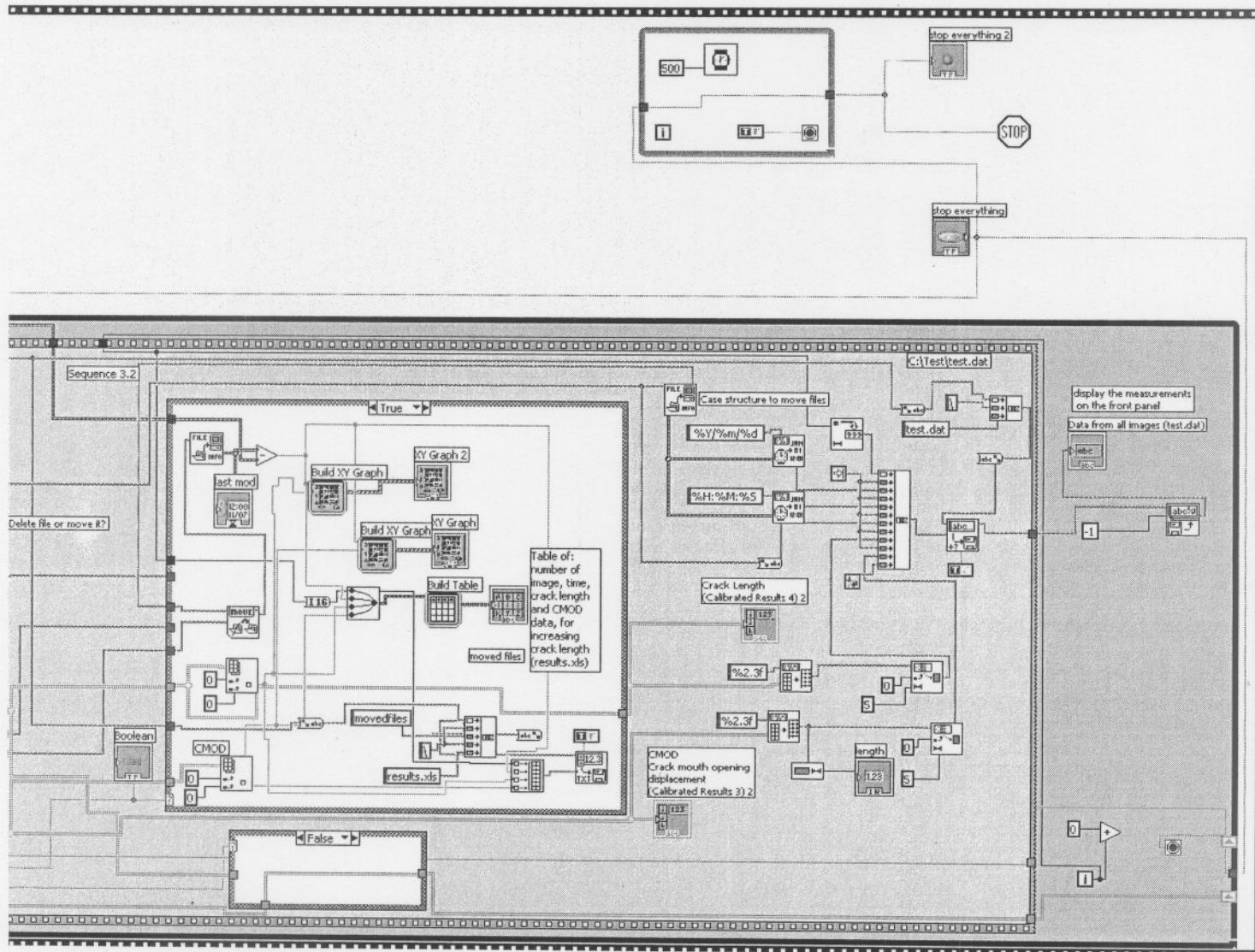
Part 2

Part 3

Part 4







C.3 Post-processing (CGMPostProc.vi)



POST PROCESSING: Secant Method

Scroll down for polynomial method

This VI is used to process data from the CGM.vi. It utilises the inputs in their respective units. Furthermore, the same input for the base directory as is the case for CGM.vi is required as input. From there the results.xls file in the "movedfiles" directory is accessed.

Dimensions

DeltaK [MPa m^{0.5}]

a [mm]

Time [s]

DeltaP [kN]

Delta P(N)

0

The `delta_min` value is used to minimize data points. It uses the value as condition to eliminate points (in order) that do not adhere to this value of change, creating a list with selected data. Its purpose is to see what effect less points have.

REQUIRED INPUTS

 $W(m)$

0

0

 $B(m)$

0

Pm

Figure 1

0

$$P_{\min}(N)$$

0

U

Freq (Hz)

100

301 (cont)

(initial crack length)

100

0

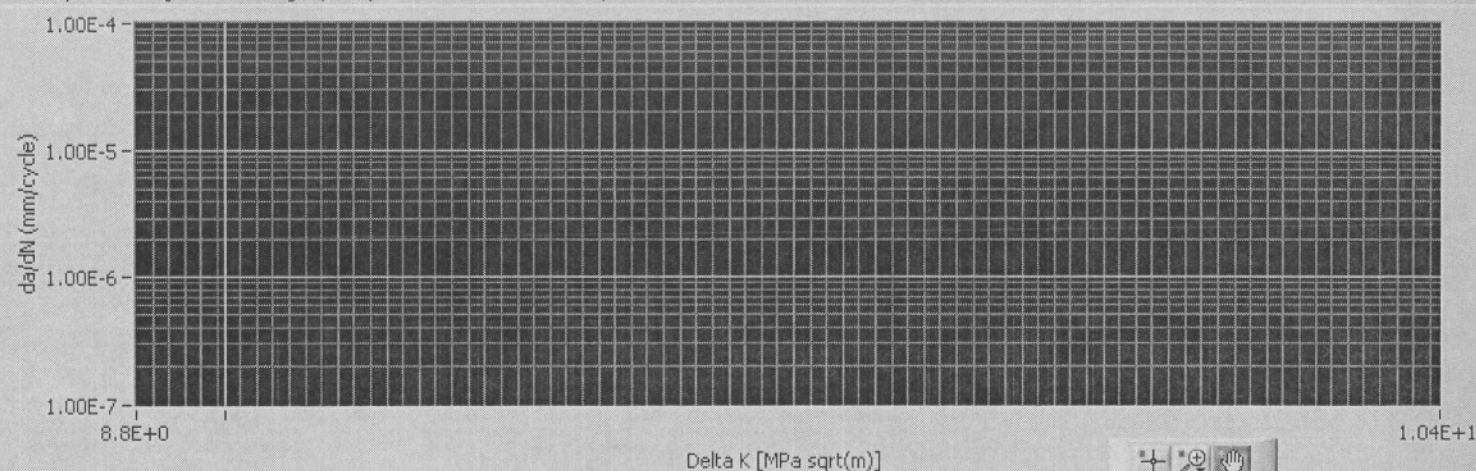
da min value (mm)

1 EE 9

all rows, #, time, crack length, CMOD

[illegible]

Graph of change in crack length per cycle versus stress intensity factor

[illegible]

POST PROCESSING: Polynomial Method

N and a

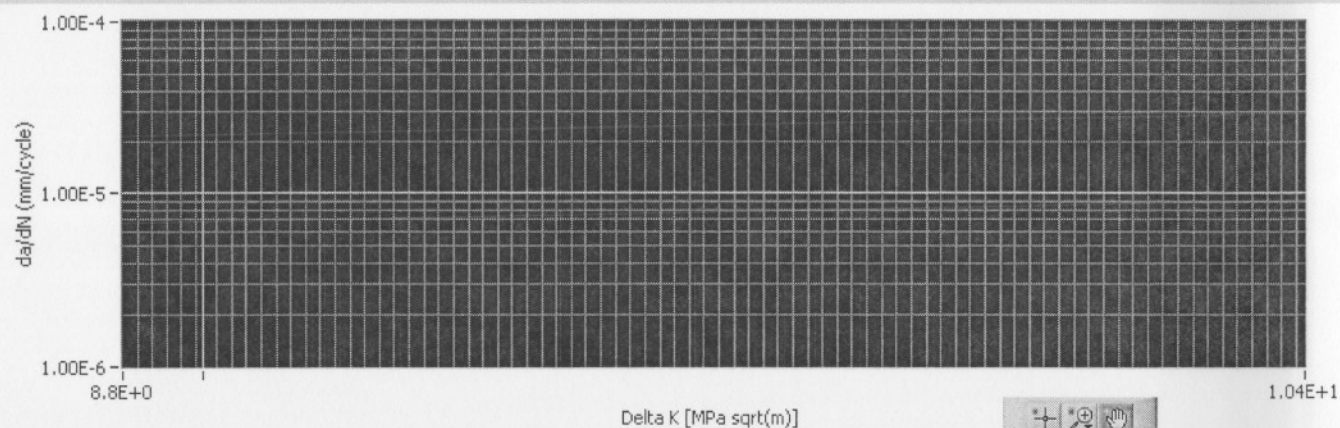
all rows, #, time, crack length, CMOD 2

[illegible]

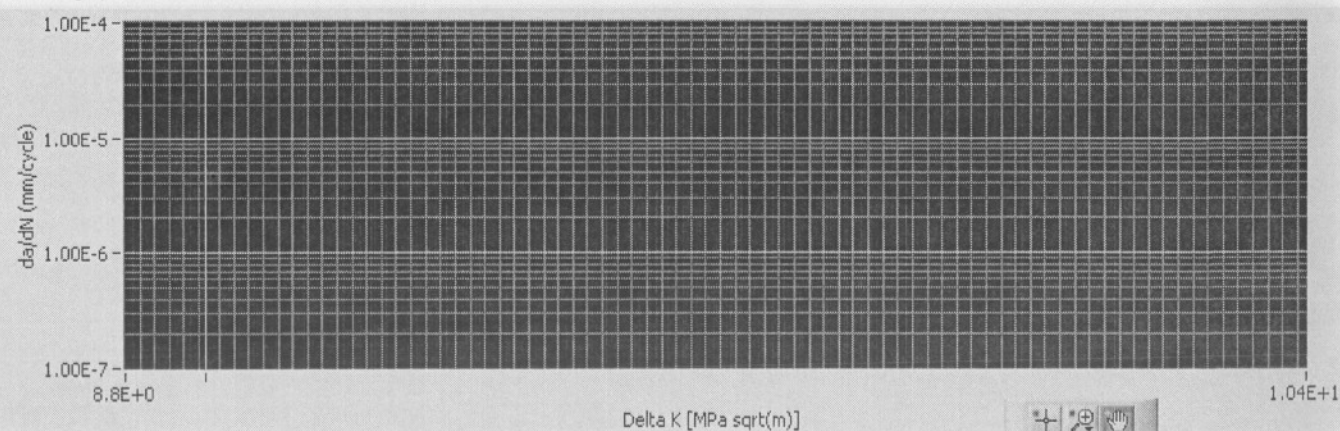
deltaK 2

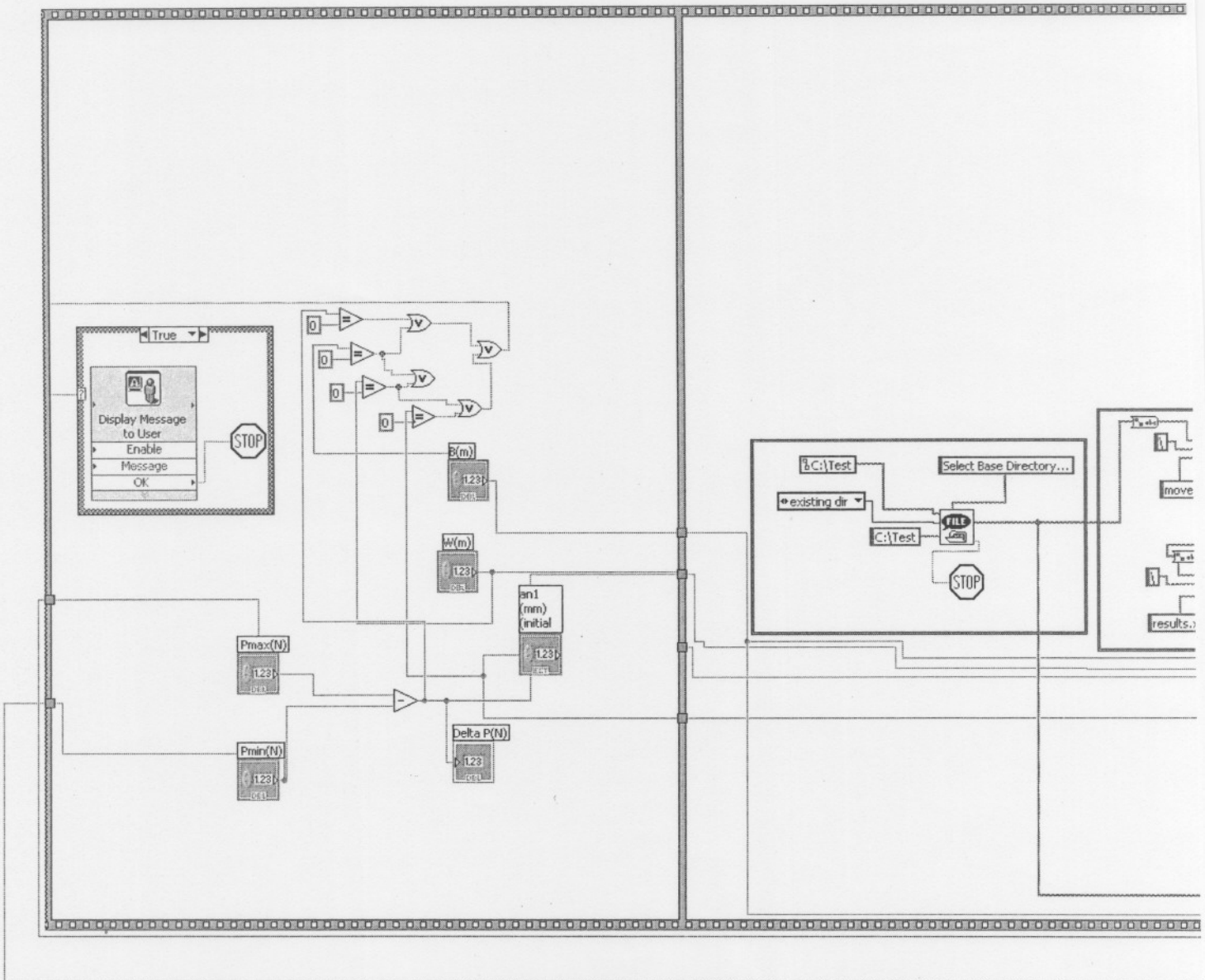
da/dN 2

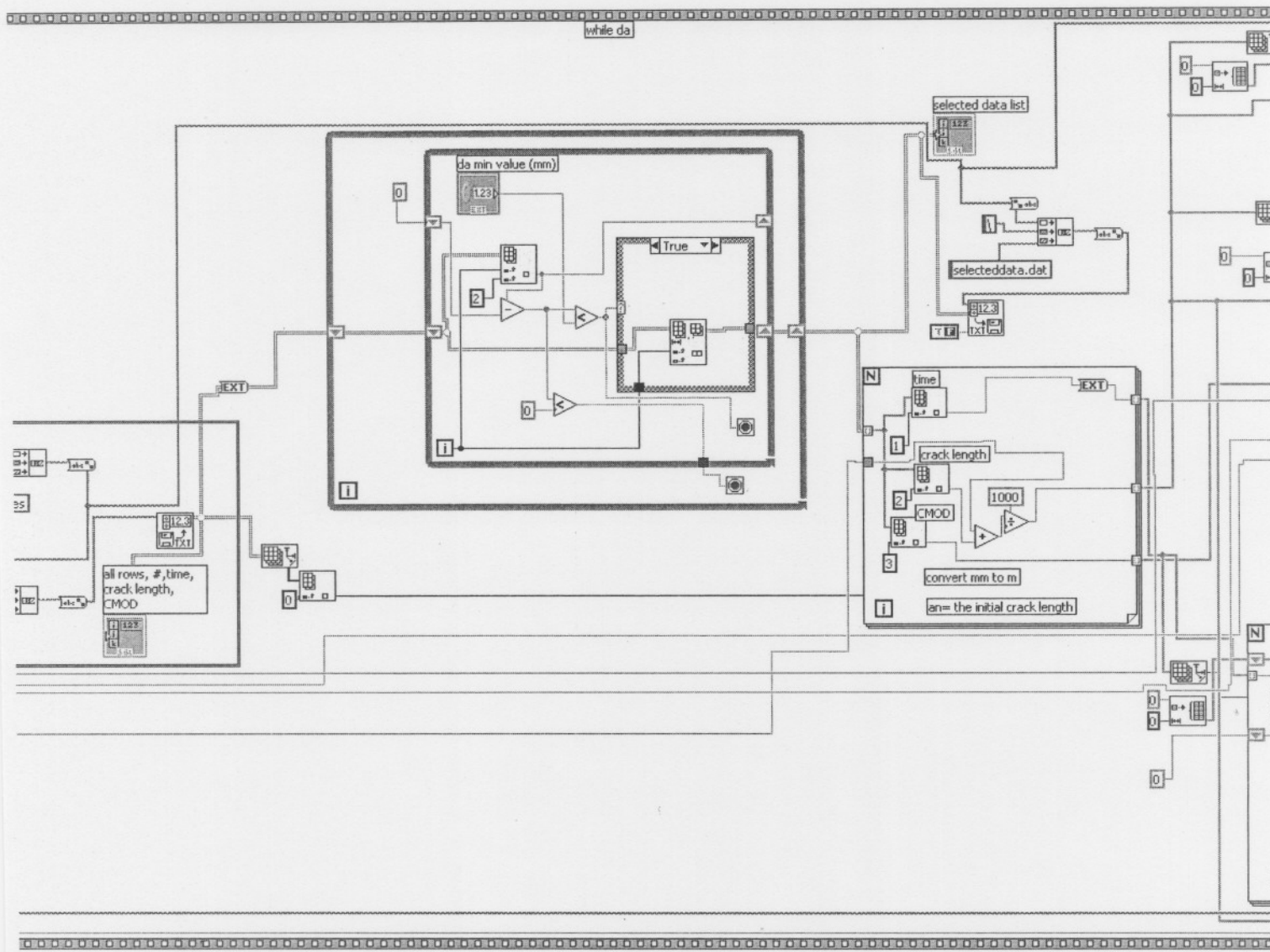
Graph of change in crack length per cycle versus stress intensity factor polynomial 7 point method

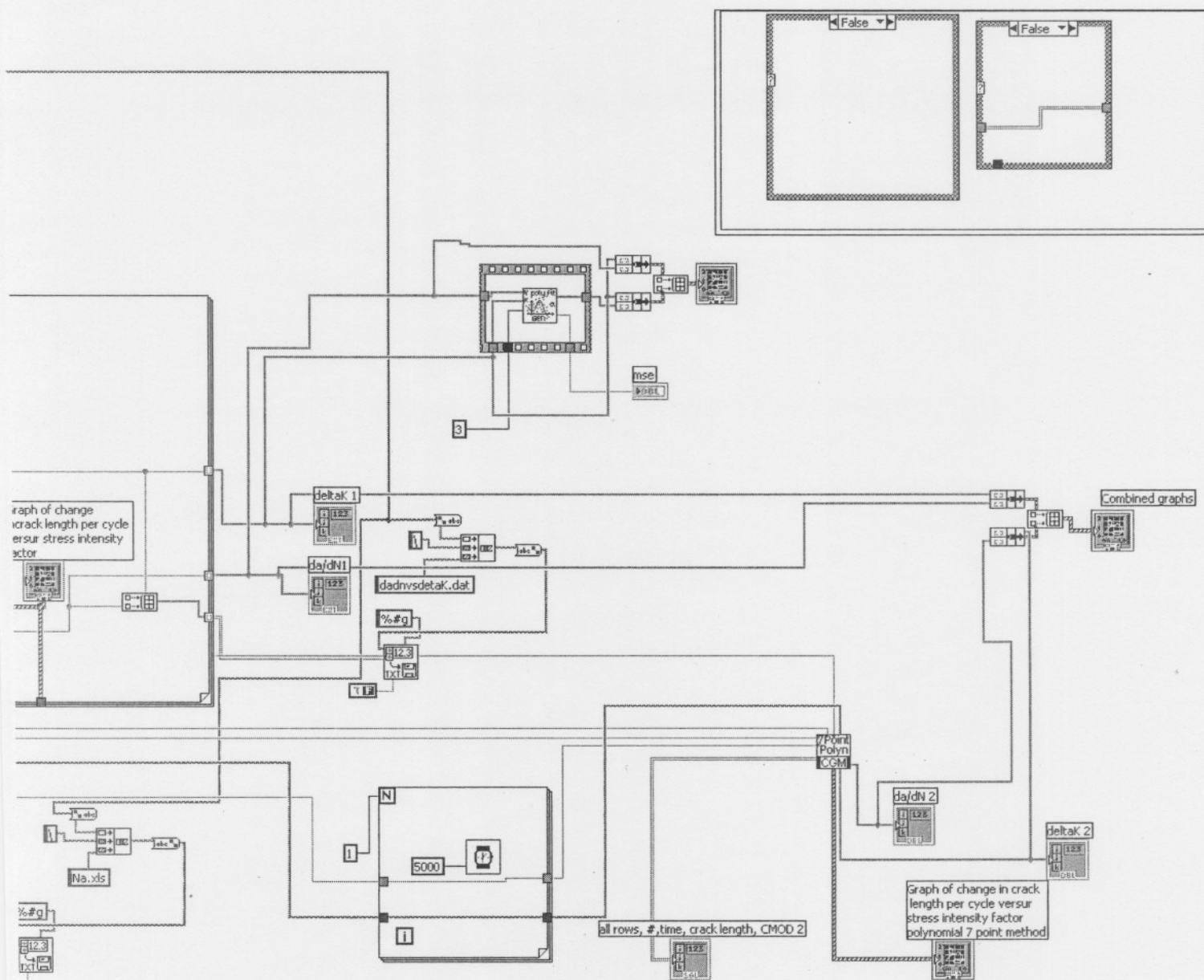


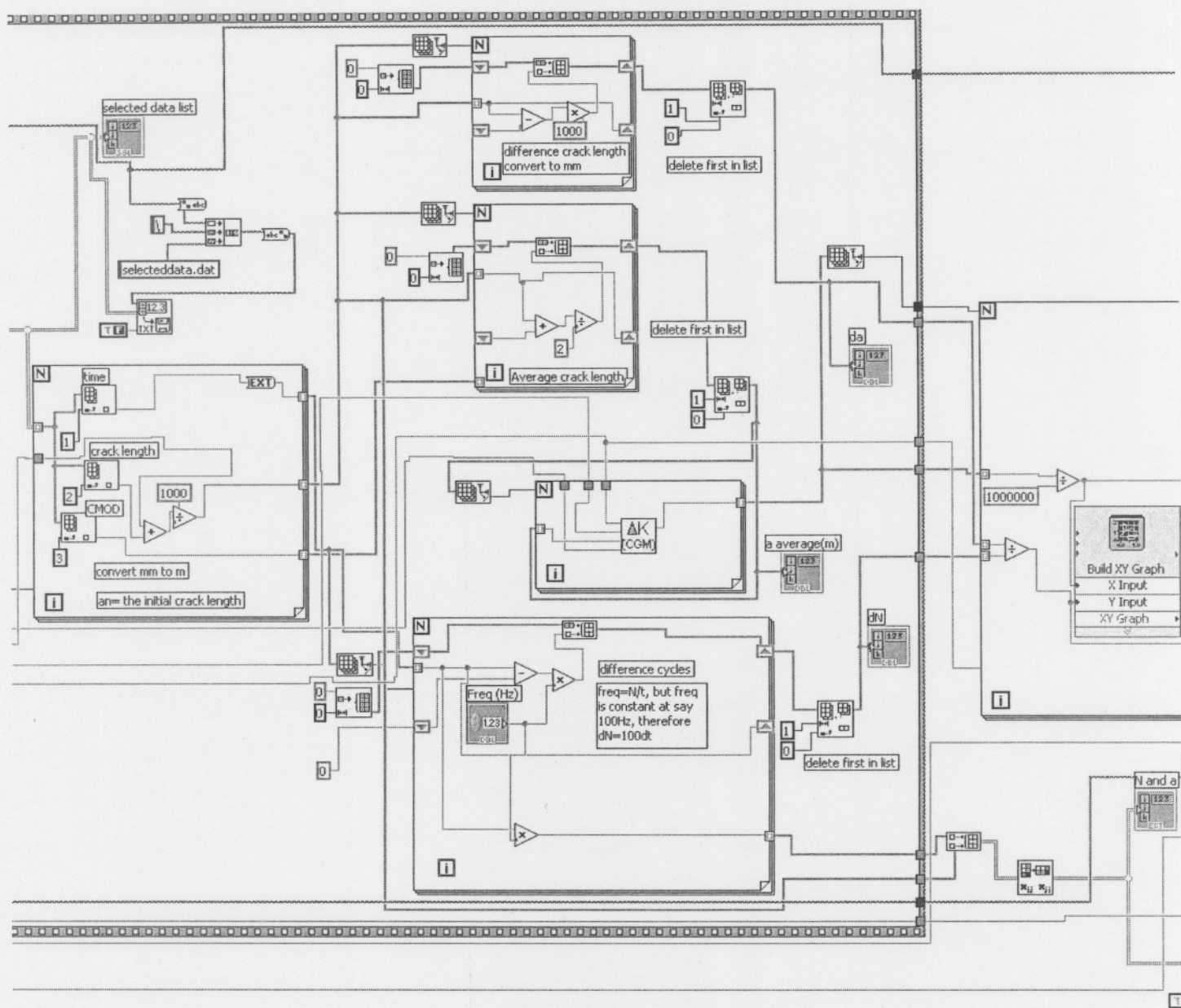
Combined graphs



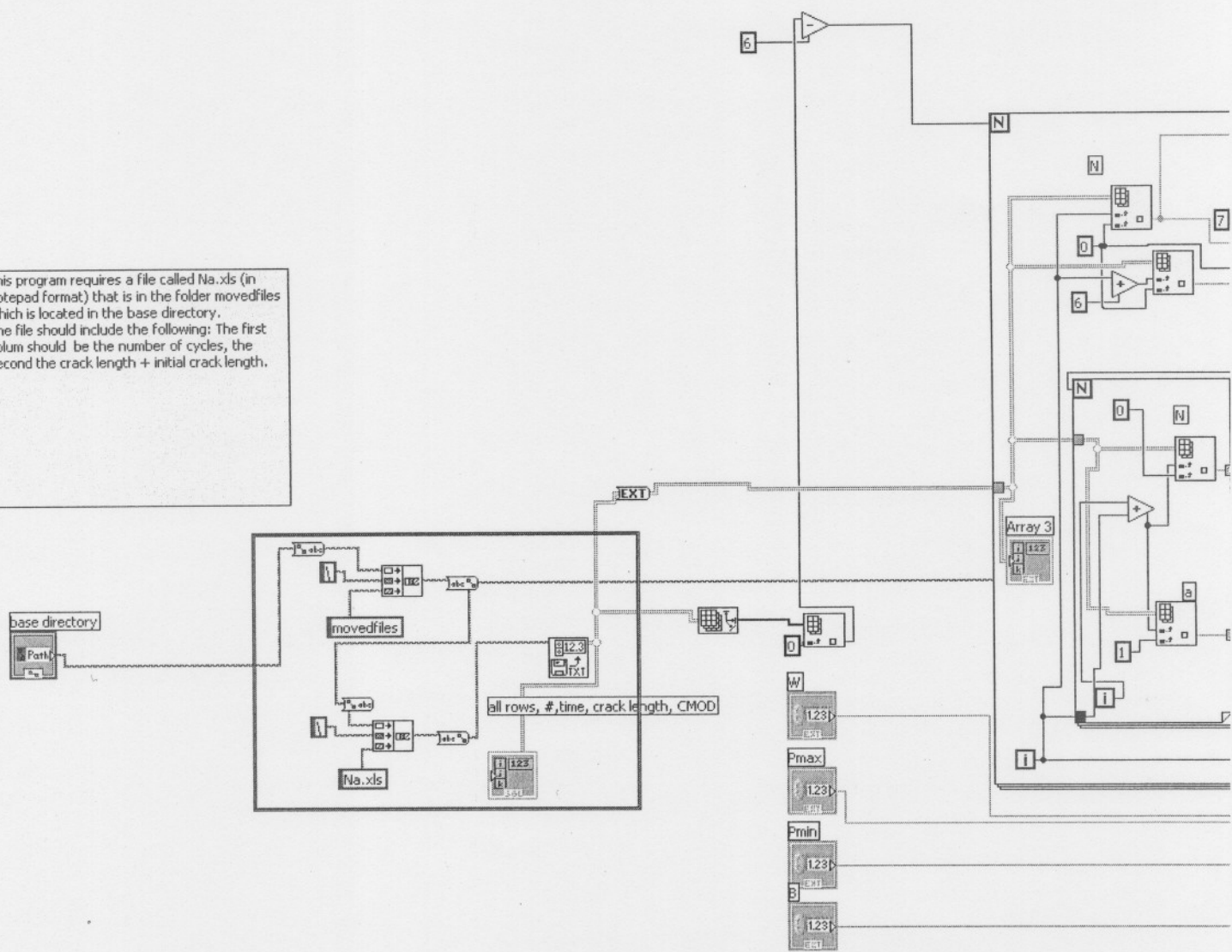


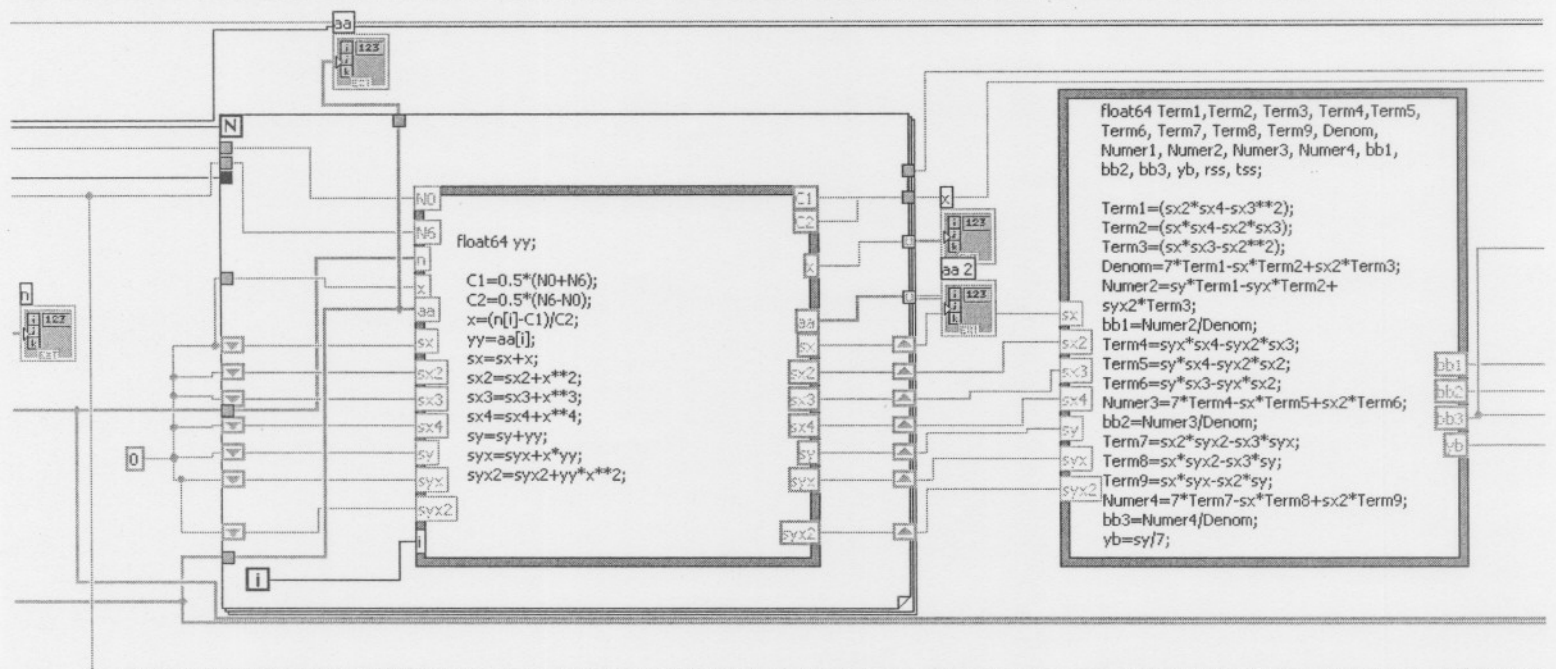


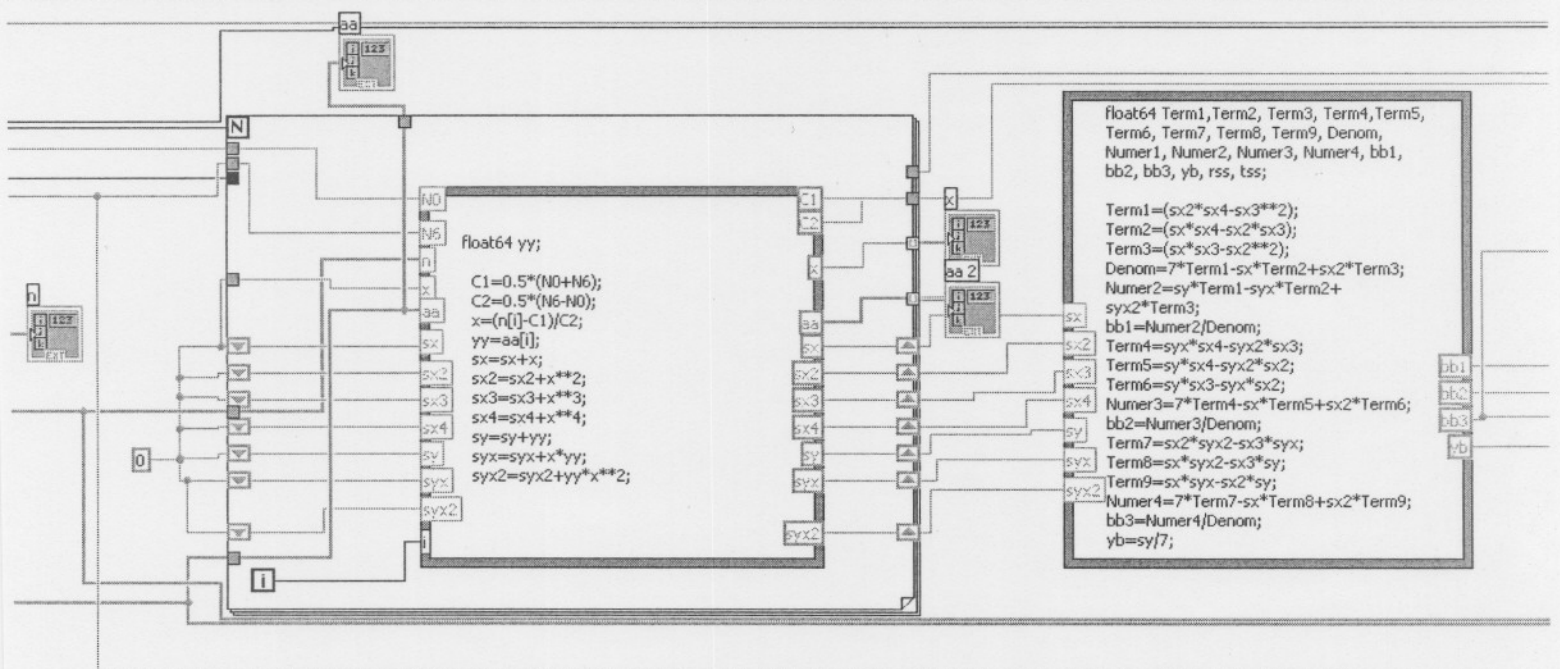




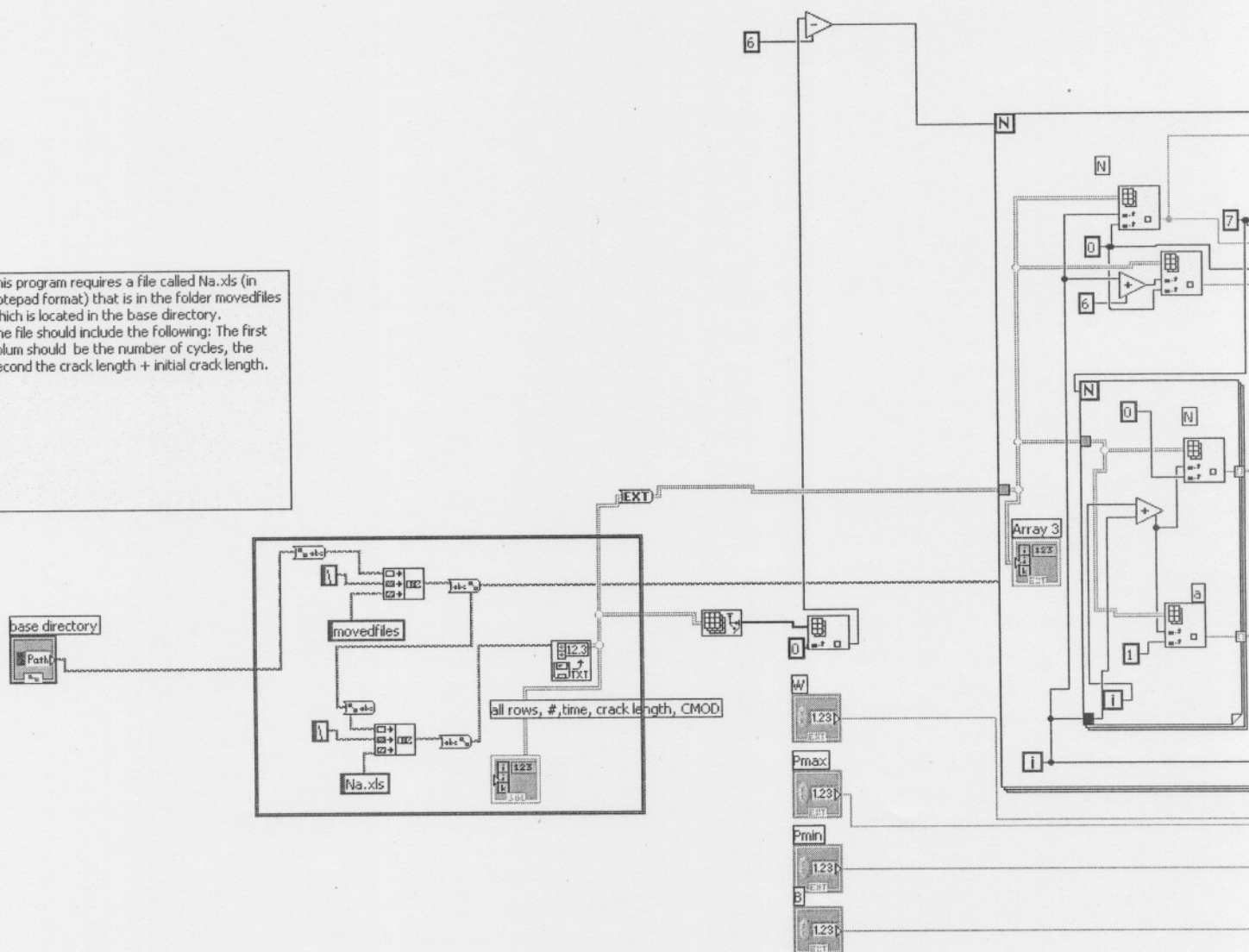
This program requires a file called Na.xls (in notepad format) that is in the folder movedfiles which is located in the base directory. The file should include the following: The first column should be the number of cycles, the second the crack length + initial crack length.

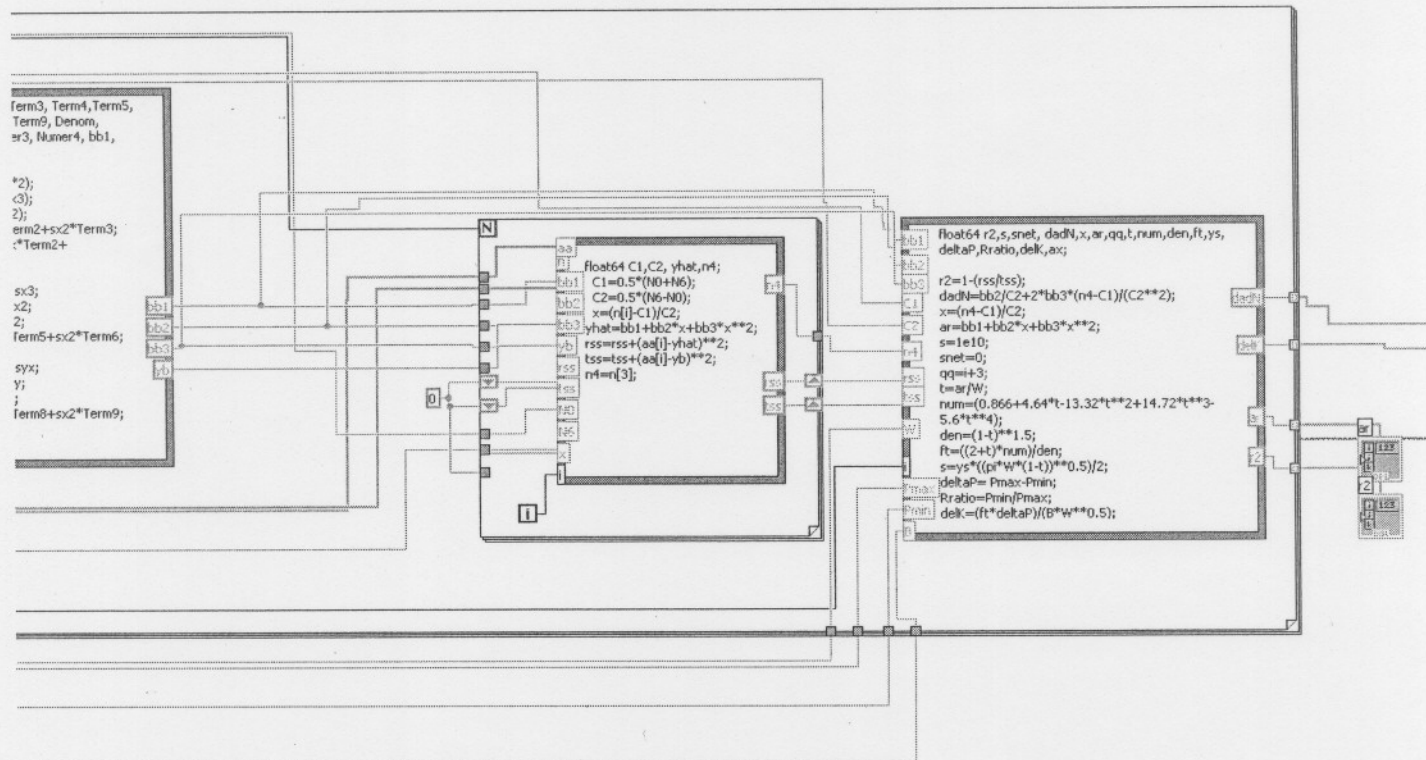


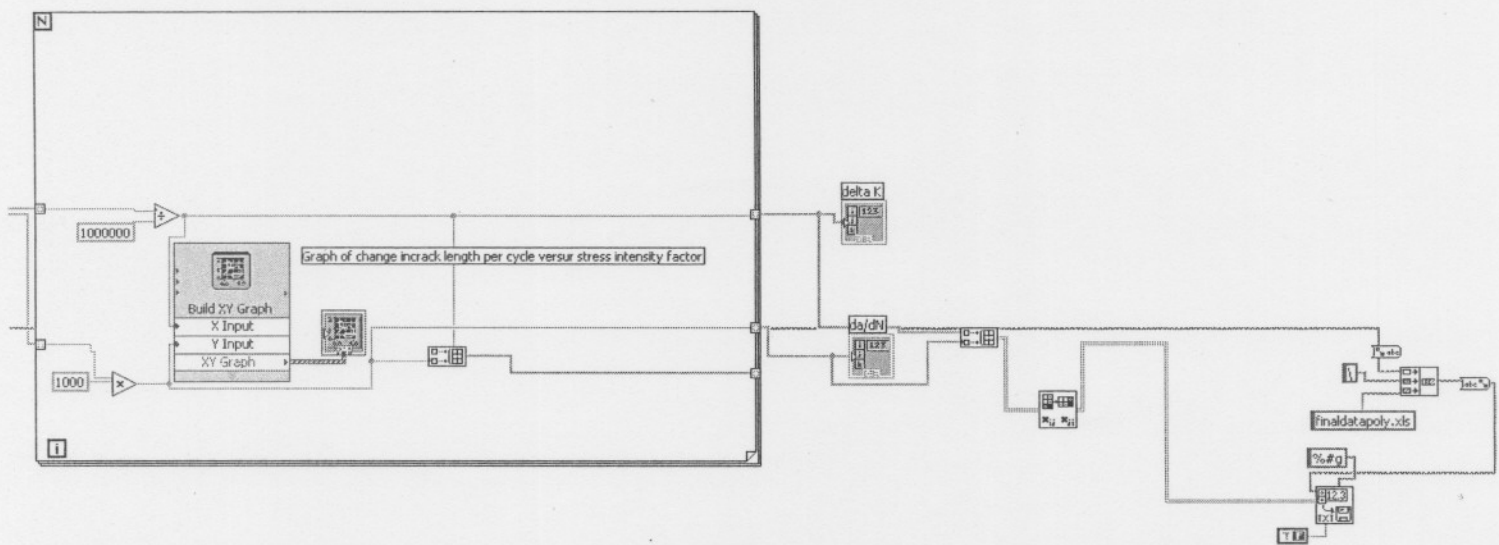




This program requires a file called Na.xls (in notepad format) that is in the folder movedfiles which is located in the base directory.
The file should include the following: The first column should be the number of cycles, the second the crack length + initial crack length.







APPENDIX D - CT-Specimen

D.1 Specimen Geometry

The following dimensions are for a CT-specimen used in ASTM E 647 (2002):

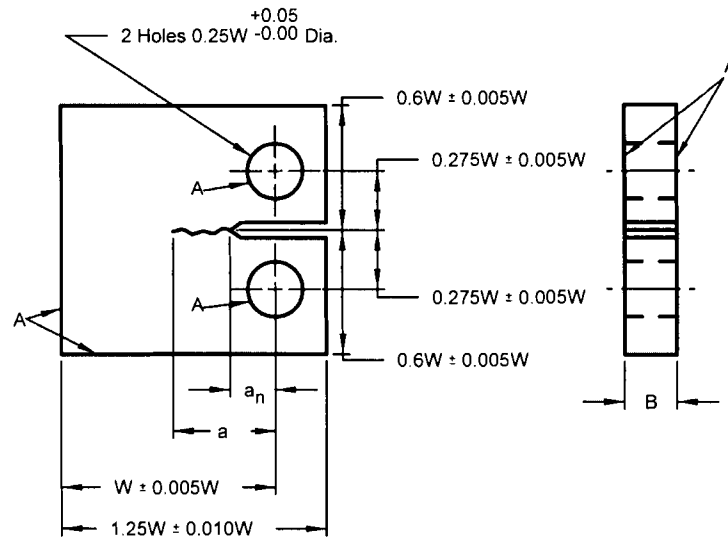


Figure D 1: Standard Compact Tension (CT) specimen for FCGR testing (modified after ASTM E647, 2002:11).

Figure D 1 has the following properties:

- Dimensions are in millimetres:
- A – surfaces shall be perpendicular and parallel as applicable to within $\pm 0.002 W$, TIR:
- The intersection of the tips of the machined notch (a_n) with the specimen faces shall be equally distant from the top and bottom edges of the specimen within $0.005 W$: and
- Surface finish, including holes shall be 0.8 or better.

ASTM furthermore recommends the following:

- The thickness of the specimen: $\frac{W}{20} \leq B \leq \frac{W}{4}$; and
- The suggested minimum dimensions: $W = 25 \text{ mm}$, $a_n = 0.20 W$.

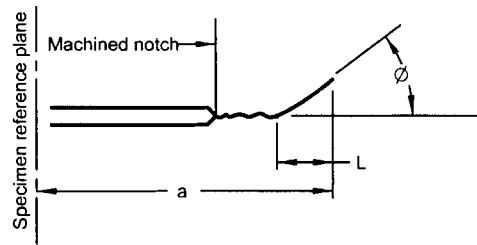


Figure D 2: Out of plane cracking limits (ASTM E647, 2002:8).

Figure D 2 illustrates the boundaries that exist with regards to crack growth and its direction. The validity of the crack is determined by the following:

- Valid if $\phi \leq 10^\circ$;
- Report if $10^\circ \leq \phi \leq 20^\circ$; and
- Invalid if $\phi > 20^\circ$ for $L \geq 0.1 W$.

D.2 Specimen Preparation

The specimen preparation after cutting to size is done through a six to seven step finishing process. Depending on the indentations on the surface, an optional first step of using a diamond grinding wheel to smoothen the specimen is used. The specimen is then sanded down to a 400 grain sanding paper (mounted on rotating sanding disks) until a uniform surface on both sides is achieved from where the crack will be monitored. It is followed by 600, 800 and 1 000 grain sizes where each step reverts back to the previous one if it is found to have a deeper scratch than which the current roughness can break through. The specimen is then polished to a finish of 6 and finally 1 μ m. Softer materials may require an even finer surface finish.

D.3 References

ASTM E647. 2002. *Standard Test Method for Measurement of Fatigue Crack Growth Rates*. 42p.

APPENDIX E - Connection

E.1 BNC-Cable Numbering

The six outputs from the Instron-1603-controller are as listed:

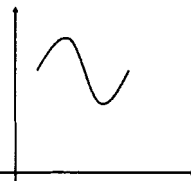
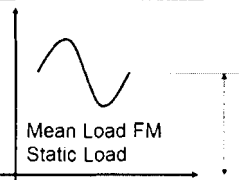
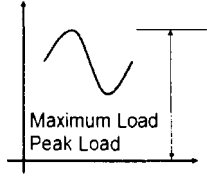
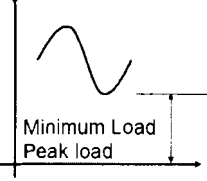
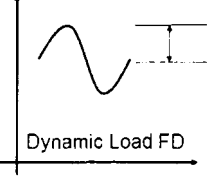
Nr.	Label	Description	Indicator	Indicated on controller display (Potential difference.)
1	SS	Syncho signal		$\pm 5V$ for 100%
2	HZ	Resonance frequency	HZ	$\pm 1V$ for 100%
3	FM	Mean load		$\pm 1V$ full scale
4	F _{MAX}	Maximum load FM + FD		$\pm 2V$ full scale
5	F _{MIN}	Minimum load FM - FD		$\pm 2V$ full scale
6	FD	Dynamic load. The load added to the mean load		$\pm 1V$ full scale

Table E 1: BNC cable output and description.

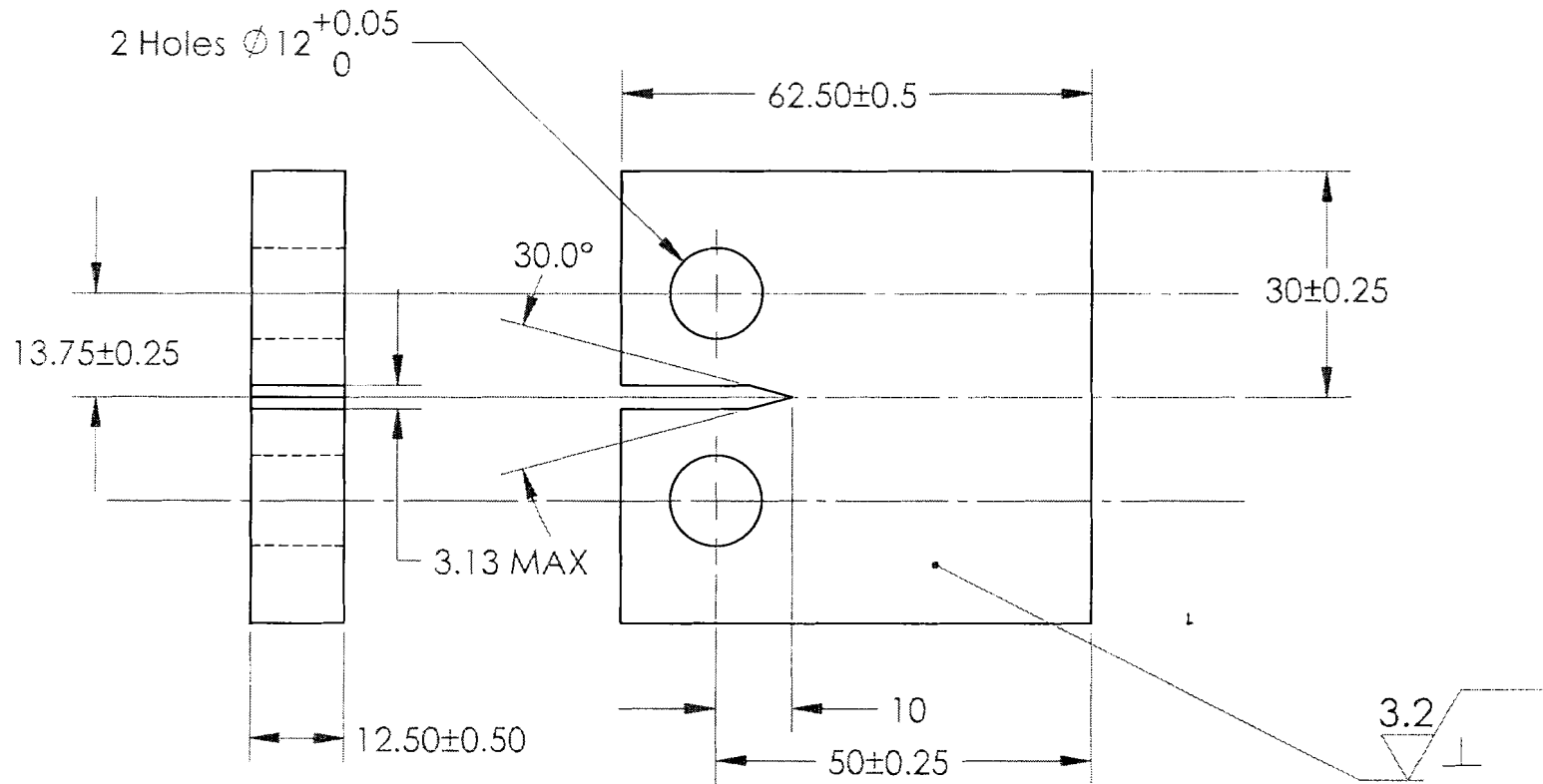
The BNC-cables are connected in the following order:

Connector block label	Connects to label
AI2 – AO7	SS
AI3 – AO6	HZ
AI4 – AO5	FM
AI5 – AO4	F _{MAX}
AI6 – AO3	F _{MIN}
AI7 – AO2	FD

Table E 2: BNC-cable connection to connector block.

APPENDIX F - Additional Test Data

F.1 Mild Steel Specimen



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH: 3.2

TOLERANCES: LINEAR: 0-6 ± 0.2
6-30 ± 0.5
30-100 ± 0.8

ANGULAR: $\pm 1\%$

FINISH:

REVISION

NAME	TELEPHONE	DATE
DRAWN HANS KAUFFMANN	0826886946	14/2/2005

TITLE: COMPACT TENSION SPECIMEN

CHK'D

APPV'D

MFG

Q.A

MATERIAL: MILD STEEL

DWG NO.

CT SPECIMEN 3

A4

SCALE: 1:1

SHEET 1 OF 1

APPENDIX G - Software (CD)

G.1 CD-Content

Item	Description	Location
CGM.vi	Main program.	D:\LabVIEW files
CGMviwithoutDelete.vi	Main program without delete function.	D:\LabVIEW files
CGMviwithoutDeletenoDAQ.vi	Main program without delete function and without data acquisition.	D:\LabVIEW files
PostProc.vi	Post-processing file.	D:\LabVIEW files
Calibration.doc	Procedure for Image Calibration.	D:\Manuals
Operating manual.doc	Operating manual.	D:\Manuals
Calibration.scr	Calibration file.	D:\NiVision
CheckImage.scr	Additional file to check the validity of the image.	D:\NiVision

Table G 1: Description of CD-content.