NUMERICAL ANALYSIS OF FATIGUE BEHAVIOR OF WELDED CFCHS T-JOINTS

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ABSTRACT: Fatigue life assessment of welded connections [illegible]
filled CF chord member subj[illegible]
in fatigue life assessment of [illegible]
describes a methodology for [illegible]
T-joints based on a finite element [illegible]
interface elements [illegible]
T-joints is also established [illegible]
fatigue life and hot spot stress [illegible]
shallow crack stage. The propos[illegible]
T-joints

Keywords: Concrete filled [illegible] Fracture [illegible]
Finite element analysis

INTRODUCTION

Concrete filled steel tubes [illegible]
China, concrete filled circul[illegible]
arch truss bridges. One examp[illegible]
a m main span. In the CFCHS arc[illegible]
members and the brace members [illegible]
while the braces are unfilled [illegible]
that the concrete infill ca[illegible]
the stiffness near the inter[illegible]
loads may cause fatigue failu[illegible]
and welding defects. The weld[illegible]
to fatigue cracking since the[illegible]
important issue in designing welded CFCHS joints.

Extensive research has been co[illegible]
e.g. [ ]. The hot spot stress [illegible]
joints [ ], where SCF stress [illegible]
strength curves are required [illegible]
to welded CFCHS joints because [illegible]

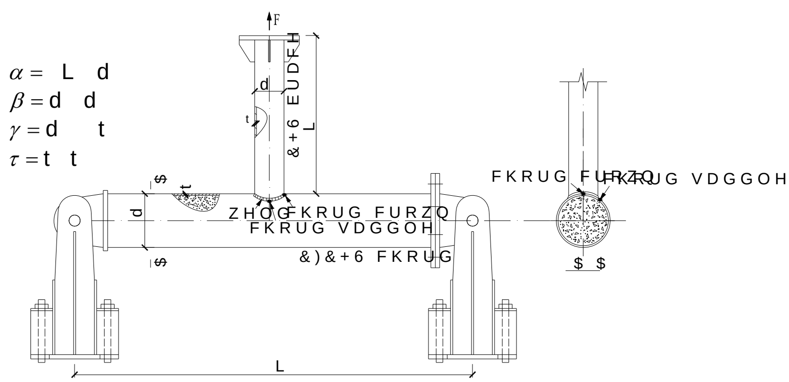
VRPH UHVHDUFK RQ &)&+6 ... FRQFUHWH ... &)6+6 OHYHO ... WKH
. MRLQWV > @ &)6+6 7 MRLQWV >@ +RZHYHU &)&+6 ... PDMRULW\
HQRXJK H[SHULPHQWDO GDWD WR HVWDEOLVK ... 6&)
WXEXODU MRLQWV

7KLV SDSHU SUHVHQWV D IUDFWXUH IDWLJXH ...
ZKLFK LQYROYHV WKH GHWHUPLQDWLRQ ...
FUDFN JURZWK PRGHO 7KH VWUHVV ...
DQG JHRPHWU\ > @ $ EULHI VXPPDU\ ...
VWUHVVHV DQG IDWLJXH OLIH RI ZHOGHG &)&+6 7 ...
DVVXPSWLRQV DERXW WKH FUDFN ...
PHFKDQLFV 7R GHWHUPLQH WKH ...
SDUDPHWHU WUDQVIRUPDWLRQ PHWKRG ...
ZHOGHG &)&+6 7 MRLQW ZLWK VXUIDFH FUDFN ...
SURSDJDWLRQ EHKDYLRU IURP QXPHULFDO ...
RI ZHOGHG &)&+6 7 MRLQWV DJUHHV ...

%5,() 6800$5< 2))$7,*8(7(676 21 :(/'(' &)&+6 7 -2,176

7KH GLPHQVLRQV DQG JHRPHWU\ RI ZHOGHG &)&+6 7 ...
7DEOH $ WRWDO RI WHQ VSHFLPHQV ...
RUGHU WR VWXG\ WKHLU HIIHFW ...
EUDFH LQ WKH MRLQW ZDV VWHHO ...
ZHOGLQJ ZLWK IXOO SHQHWUDWLRQ ...
FRQFUHWH ZKLOH WKH EUDFH ZDV XQILOOHG

6WDWLF WHVWV LQ WKH HODVWLF ...
8QLYHUVLW\ WR REWDLQ KRW VSRW VWUHVV ...
GHILQHG DV WKH UDWLR RI KRW ...
VSHFLPHQV)RU WKH VWDWLF ...
ZDV VLPSO\ VXSSRUWHG VHH)LJXUH ...
PD[LPXP 6&) OLVWHG LQ 7DEOH RFFXUUHG DW WKH FKRUG FURZ



)LJXUH :HOGHG &)&+6 7 MRLQW 6SHFLPHQ DQG 6WD

7DEOH 'HWDLOV RI 7HVW 6SHFLPHQV

-RLQW	d × t PPîPP	d × t PPîPP	1RQGLPHQVLRQDO JHRPHWULFDO SDUDPHWHUV β d d	γ d t	τ t t	6WHHO *UDGH	&RQFUHWH *UDGH
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&
&)&+6	î	î				4	&

1RWH %RWK WKH QHVVH DQG VWRU6WHHO 4 DQG WKH3DLPD -RXOHV UHVSHFWLYHO\ 7KH FXEH FRPSUHVVLYH VWUHQJWK RI DQG 03D UHVSHFWLYHO\

7DEOH ([SHULPHQWDO 6&) DQG)DWLJXH /LIH RI 7H

-RLQW	0D[LPXP 6&)	$[LDO IRUFH UDQJH N1	)DWLJXH OLIH 1
&)&+6			
&)&+6			
&)&+6			
&)&+6			
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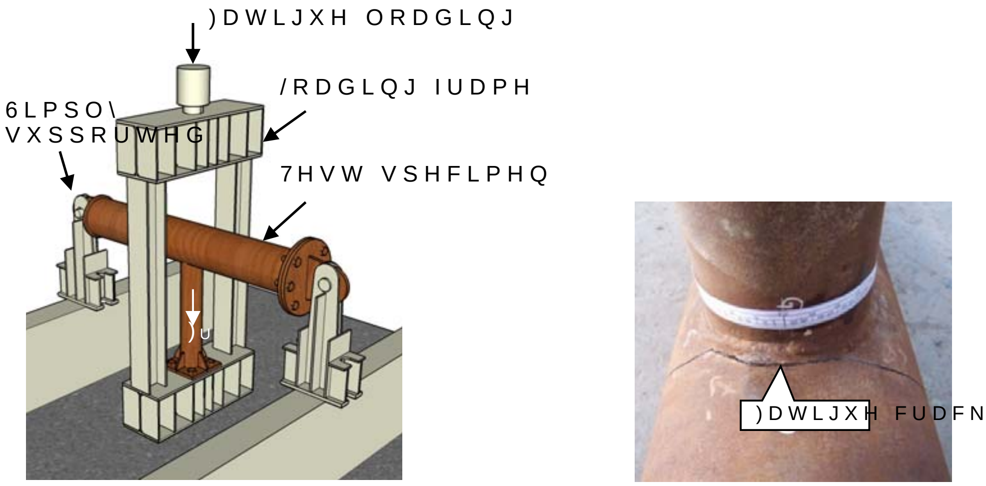
&RQVWDQW DPSOLWXGH IDWLJXH ORDGLQJ ZDV DSSOLHG WR WKH ZHOGHG &)&+6 7 MRLQWV 7KH EUDFH ZDV VXEMHFWHG WR D[LDO F\FOLF ORDGLQJ IUHTXHQF\ RI +] 7KH VWUHVV UDWLR ZDV WR 6HHLQJ WKDW WKH WKH EUDFH ZDV UHYHUVHG DQG D ORDGLQJ WKDW D SXVK IURP WKH IDWLJXH LQ)LJXUH 7KH DSSOLHG D[LDO IRUFH UDQJH LV JLYHQ LQ 7DEOH

$ W\SLFDO GDPDJH SDWWHUQ ZLWK &)&+6 7 MRLQWV LV VKRZQ LQ)LJXUH LQLWLDWHG DW RU QHDU WKH FKRUG VWUHVV L H WKH SRVLWLRQ RI PD[LPXP VWUHVV SURSDJDWHG DORQJ WKH ZHOG FLUFXPIHUHQFH 7KH IDWLJXH OLIH

7DEOH ZKLFK ZLOO EH XVHG WR XFKLHFJN ... WKH WKHRU\ RI IUDFWXUH PHFKDQLFV ... IDWLJXH LQGXFHG FUDFN IXOO\ SHQHWUDWHV ... FRPPRQO\ DFFHSWHG IDWLJXH IDLOXUH ... UHSRUWHG LQ WKH UHIHUHQFH > @



)LJXUH)DWLJXH 7HVW 6HWXS ... &UDFN

180(5,&$/ 6,08/$7,21 678'<

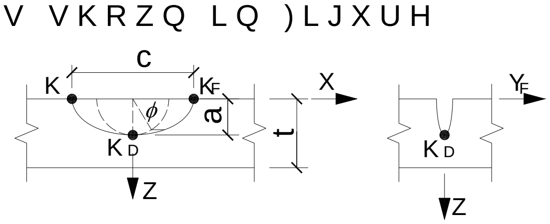
7KLV VHFWLRQ SUHVHQWV WKH QX... LQFOXGHV DVVXPSWLRQV IRU IDWL... PRGHO 7KLV QXPHULFDO DQDO\VLV ... RI &)&+6 7 MRLQWV

$VVXPSWLRQV IRU)DWLJXH &UDFN /RFDWLRQ DQG 6KDS...

,Q RUGHU WR IDFLOLWDWH QXPHU... DQG FUDFN VKDSH RI WKH ZHOGHG &)&+6 7 MRLQWV DUH EDVHG RQ ... IDWLJXH VWUHQJWK DQG REVHUYHG IDWLJXH EHKDYLRU

3.1.1 Initial crack location and size

7KH VXUIDFH FUDFN LV DVVXPHG ... FRQFHQWUDWLRQ IDFWRU 7KLV ... RI WKH &)&+6 7 MRLQWV¶ FKRUG VX... DVVXPHG WKDW WKH GHHSHVW SRLQW ... WKH FKRUG DV VKRZQ LQ)LJXUH



)LJXUH 6FKHPDWLF ... 6XUIDFH &UDFN 0RGHO

,Q WKH +6(GRFXPHQW > @ VODJHLQWUXVLRQV WR DUH PRVW LQFLGHQW...
W\SLFDO VL]HV DW WKH ZHOG WRH ... DUH DVVXPHG ... WKH LQLWLDO ...
DVVXPHG DV PP IRU WKH LQLWLDO FUDFN VKDSH

3.1.2 Crack shape

%DVHG RQ WKH NQRZOHGJH RI OLQHDU HODVWLF IUDFWXUH PHFKDQLFV ...
IRU WKH ZHOGHG &)&+6 7 MRLQWV ...)LJXUH ...
VHPL HOOLSWLFDO ...
SURMHFWHG LQWR D SODQH ... WKH ...
VKDSH DV VKRZQ LQ)LJXUH 7KH ...
SHUSHQGLFXODU WR WKH VXUIDFH ...
SURSDJDWLRQ ,Q WKLV VWXG\ ...
DQG WKH FUDFN HQGV UHVSHFWLYHO\ ...

)LQLWH (OHPHQW $QDO\VLV

7KH PDMRU FKDOOHQJHV HQFRXQWHUHG ...
ZHOGHG &)&+6 7 MRLQWV ZLWK VXUIDFH ...
PRGHOLQJ FUDFN PRGHOLQJ QRQ ...
DFFRPSOLVK WKLV XVLQJ WKH JHQHUDO ...
3DUDPHWULF 'HVLJQ /DQJXDJH ZDV ...
VFKHPH DV ZHOO DV FRQVWUXFWLQJ ...
WKH FRPSOH[SUREOHP RI PRGHOLQJ ...
LQWR D UHODWLYHO\ VLPSOH PRGHO ...

3.2.1 Modeling procedure

,Q WKLV VWXG\ WKH PHVK RI WKH ...
XVLQJ WKH $3'/ FRGH IRU D JRRG ...
DQG FRPSDWLELOLW\ RI WKH PHVK ...
SURFHGXUH LV JLYHQ LQ)LJXUHV ...

D 7 EXWW ZLWK VXUIDFH FUDFN ... &+6 ...
VXUIDFH RI D TXDUWHU RI ...

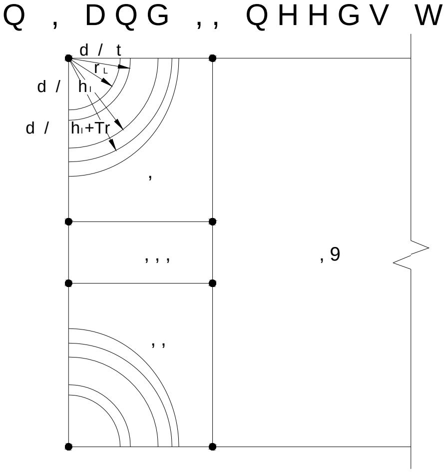
G 4XDUWHU &+6 MRLQW H LQILOOHG ...
)LJXUH ,OOXVWUDWLRQ RI)LQLWH (OHPHQW 0RGH...

67(3 7KH ILUVW VWHS LQ WKH PRGHOOLQJ SURFHVV LV WKH
VHPL HOOLSWLFDO FUDFN GHILQHG E\ WZR GLIIHUHQW UHFKROGV
ZDOO WKLFNQHVV &UDFN WLS VLQJXODULW\ HOHPHQWV DUH XVHG
EUDFH PHPEHU LQ WKH 7 MRLQW
67(3 7KH 7 EXWW SODWH LV WKHQ GLVFUHWL]HG
V\PPHWU\ RI WKH 7 MRLQW DQG DSSOLHG ORDG
67(3 $ IODW SODWH PRGHO IRU WKH FRQQHFWLQJ
PRGHO IURP 67(3 E\ PHUJLQJ WKH FRPPRQ QRGHV
67(3 7KH FKRUG SODWH PRGHO LV EXLOW
β γ τ t RI WKH MRLQW GHILQHG
67(3 &RQFUHWH HOHPHQWV DUH DGGHG
WKH LQWHUIDFH PHVK RI WKH FRQFUHWH
LQWHUIDFH RI WKHVH WZR PDWHULDOV

3.2.2 Geometric transformation

*HRPHWULF WUDQVIRUPDWLRQ LV HPSOR\HG
PDLQWDLQLQJ WKHLU WRSRORJLFDO
IRUPXODV KDYH EHHQ GHULYHG DQG
LQ WKLV VWXG\ &UDFN WLS VLQJXODULW\
WKH $16<6 HOHPHQW OLEUDU\ ,Q
MRLQW VL]HV KDYH EHHQ FKRVHQ
EHWZHHQ WKH VWHHO FKRUG PHPEHU

)RU KLJK TXDOLW\ PHVK JHQHUDWLRQ
UHJLRQV DV VKRZQ LQ)LJXUH
r_L KDYH EHHQ GUDZQ
UHSUHVHQWV WKH FKRUG
GLIIHUHQW WUDQVIRUPDWLRQ
h_f LV WKH ZHOG WRH
IRU ERWK 5HJLRQ , DQG ,, QHHGV WR EH V\PPHWULFDO

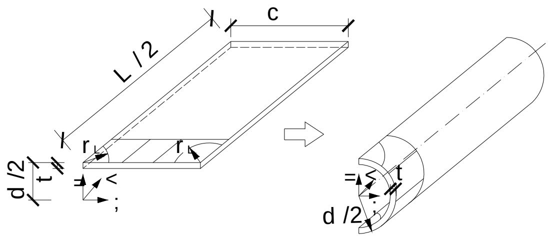


)LJXUH)RXU 5HJLRQV IRU)LQLWH

,W LV QRWHZRUWK\ WKDW WKH
VXUIDFH RI WKH FRQFUHWH FRLQ
LW PD\ OHDG WR QRQ
$16<6 PRGHO GXH WR WKH LQLWLDO
IROORZLQJ IRUPX

3.2.2.1 Geometric transformation for chord

$Q XQIROGHG SODQH VXUIDFH PHVK RI)LJXUH IRUP ZKLFK FRPSRQHQW FXUYHG VXUIDFH PHVK XVLQJ (TV DQG



)LJXUH *HRPHWULF 7UDQVIRUPDWLRQ IRU &KRUG

)RU $x \le d$ h_f Tr DQG $r \le d$ h_f Tr VHH)LJXUH

$$\begin{cases} X = Z\,VLQ > \dfrac{d\ DUFVLQ\dfrac{X}{d} \quad \dfrac{d - Z\ c - c\ d}{t\,c} \quad \dfrac{X}{d}DUFVLQ}{Z} @ \\ Y = Y \\ Z = Z\,FRV > \dfrac{d\ DUFVLQ\dfrac{X}{d} \quad \dfrac{d - Z\ c - c\ d}{t\,c} \quad \dfrac{X}{d}DUFVLQ}{Z} @ \end{cases}$$

:KHUH d LV WKH RXWHU FLUFXPIHUHQFH DQG c LV WKH FKRUG FLUFXPIHUHQFH RI

)RU $x \ge c - d$ h_f Tr) DQG $r \le d$ h_f Tr,

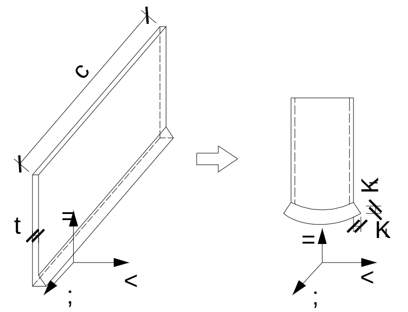
$$\begin{cases} X = Z\,VLQ > \dfrac{c - d \quad \dfrac{c - X}{d} D \quad \dfrac{d - Z\ c - c}{t\,c} U \quad F \quad c - d V \quad \dfrac{c - X}{d} L \quad Q}{Z} @ \\ Y = Y \\ Z = Z\,FRV > \dfrac{c - d \quad \dfrac{c - X}{d} D \quad \dfrac{d - Z\ c - c}{t\,c} U \quad F \quad c - d V \quad \dfrac{c - X}{d} L \quad Q}{Z} @ \end{cases}$$

)RU RWKHUV

$$\begin{cases} X = Z\,VLQ > \dfrac{X - \dfrac{d - Z\ c - c}{t\,c} X}{Z} @ \\ Y = Y \\ Z = Z\,FRV > \dfrac{X - \dfrac{d - Z\ c - c}{t\,c} X}{Z} @ \end{cases}$$

3.2.2.2 Geometric transformation for brace

$ SODWH PHVK ZLWK ZHOG LQ)LJXUH PHVK VXWLOL]LQJ (T IRUPHG LQWR



)LJXUH *HRPHWULF 7UDQVIRUPDWLRQ IRU %UDFH

)RU $Z \in d > d + h_f$ @

$$\begin{cases} X = Y\,VLQ > \dfrac{X - \dfrac{d + h_f - Y\,c - c}{t + h_f\,c}X}{Y} & @ \\ Y = Y\,FRV > \dfrac{X - \dfrac{d + h_f - Y\,c - c}{t + h_f\,c}X}{Y} & @ \\ Z = Z - d > -\sqrt{d - X} & @ \end{cases}$$

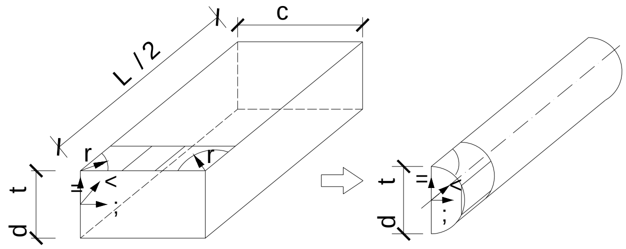
:KHUH d LV WKH LQQHU FLUFXPIHUHQFH RI FKRUG PHPEHU DW LQWHUVHFWLRQ OHQJWK LQ
RQ WKH FKRUG VLGH

)RU $Z \in d > + h_f\; d + L$ @

$$\begin{cases} X = Y\,VLQ > \dfrac{X - \dfrac{d + h_f - Y\,c - c}{t + h_f\,c}X}{Y} & @ \\ Y = Y\,FRV > \dfrac{X - \dfrac{d + h_f - Y\,c - c}{t + h_f\,c}X}{Y} & @ \\ Z = Z - \dfrac{d + L - Z}{L - h_f}\,d > -\sqrt{d - X} & @ \end{cases}$$

3.2.2.3 Geometric transformation for concrete

,Q RUGHU WR PDNH WKH QRGHV RQ WKH EUDFH DQG FKRUG IRUP D XQLIRUP PHVK
WKH H[WHUQDO VXUIDFH FRQFUHWH PHVK LQ)LJXUH LV WUD



)LJXUH *HRPHWULF 7UDQVIRUPDWLRQ IRU &RQFU

)RU $X \le d$ h_f Tr DQG $r \le d$ h_f Tr

$$\begin{cases} X = d - t \dfrac{c\, d\, \mathrm{DUFVLQ} \frac{X}{d} V}{c\, d - t} \; L \; Q \; > \quad @ \\ Y = Y \\ Z = \dfrac{Z\sqrt{d - t - X}}{d - t} \end{cases}$$

)RU $X \ge c - d$ h_f Tr DQG $c \le d$ h_f Tr,

$$\begin{cases} X = d - t \; \mathrm{VLQ} > \dfrac{c\, c - d\, \mathrm{arc} \frac{c - X}{d} \; V \; L \; Q}{c\, d - t} \quad @ \\ Y = Y \\ Z = \dfrac{Z\sqrt{d - t - X}}{d - t} \end{cases}$$

)RU RWKHUV

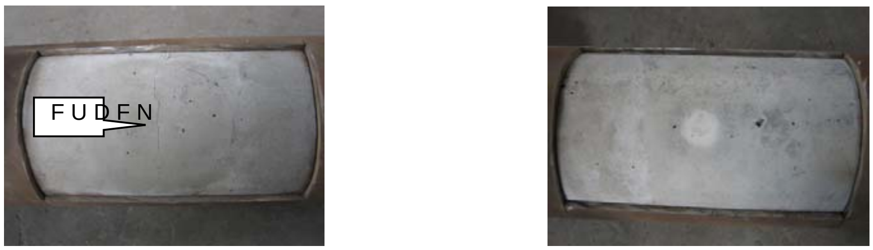
$$\begin{cases} X = d - t \dfrac{c\, X}{c\, d - t} V \; L \; Q \; > \quad @ \\ Y = Y \\ Z = \dfrac{Z\sqrt{d - t - X}}{d - t} \end{cases}$$

3.2.3 Material property and element type

,Q WKH ILQLWH HOHPHQW DQDO\VLV ... WKH $16<6 VRIWZDUH ... 3RLVVRQ¶V UDWLR DUH VHW *3D DQG > @ UHVSHFWLYH

3DUWLFXODU DWWHQWLRQ ZDV JLYHQ ... IDWLJXH ORDG DV WKLV LV LPSRUWDQW ... IDWLJXH WHVW ZDV ... FRQFUHWH ... H[SRVH WKH FRQFUHWH IRU D FORVH H[DPLQDWLRQ ...

YLVXDO VLJQ RI FRQFUHWH FUXVKLQJ RZLQJ VHRQ LQ EDVH\ XVHSH
HOHPHQW DQDO\VLV WKDW WKH FRQFUHVHWGHL LQ ILOOEX WFK RQ JDHW W
D &+6 EUDFH DQG D &+6 FKRUG DQG WKH WKRXVD DZ HHFWHG WKH LQDW
ZKHQ FRQFUHWH VWUHQJWK JUDGH DFK DQJHV WV WKH KRZ DPVHS R$O
HIIHFW RI FRQFUHWH VWUHQJWK SURSHUW\ RQ WKLH LFRQFUHWH W
EH QHJOHFWHG 7KH IDWLJXH GHIRUPDWLRQ PRGXOXV & RQFUHWH
the Design of Concrete Structures*% 7KH\ DUH VXPPDUL]HG LQ
3RLVVRQ¶V UDWLR RI FRQFUHWH LV WDNHQ DV PRGHO WKHQ
VLPXODWHG XVLQJ WKH 62/,' HOHPHQW



D &RQFUHWH H[WUXVLRQ ILEHU &RQ EUHDNLQJ H[SHULPHQW VLRQ
)LJXUH 9LHZ RI &RQFUHWH ,QILOO 'DPDJHV

7DEOH &RQFUHWH)DWLJXH 'HIRUPDWLRQ 0RGXOXV

&RQFUHWH JUDGH	&	&	&	&	&	&	&
03D							

7KH ZHOG LV PRGHOHG XVLQJ 62/,' HOHPHQW LQ FRQWDFW JHRPHWU\
GHILQHG DFFRUGLQJ WR WKH $:6 HUURU FRPSOHWHO\ PDWHULDO
WR EH WKH VDPH DV WKH SDUHQW VWHHO PHWDO

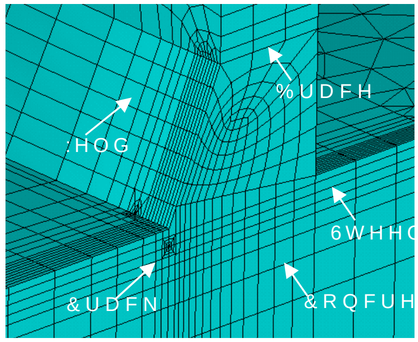
7KH FRQWDFW HOHPHQWV 7$5*(DQG &217$ DW WKH LQWHUIDFH
FRQFUHWH LQILOO DQG VWHHO FKRUG WR VLPXODWH WKH FRQWDFW E
VWHHO DQG FRQFUHWH 7KH IULFWLRQ DW WKH LQWHUIDFH

7KH FUDFN WLS VLQJXODU HOHPHQW XVHV)LQLWH HOHPHQW >LV@ E
PLGGOH QRGHV LQ WKH ZHGJH VKDSHG HOHPHQW DW WKH FUDFN WLS LQ
RUGHU WR PRGHO WKH VLQJXODULW\ 6LQFH WKLV W\SH RI HOHPHQW
ZHGJH VKDSHG VLQJXODU HOHPHQW ZDV LPSOHPHQWHG E\ WKH
SURJUDPPLQJ ODQJXDJH

)LJXUH &UDFN 7LS 6LQJXODU (OHPHQW

,Q RUGHU WR DFFXUDWHO\ VLPXODWH WKH VWUHVV LQ WKH FUDFN
UHJLRQ PRUH WKDQ IRXU OD\HUV RI HOHPHQWV LQ WKH WKLFNQHVV
DQG WKUHH OD\HUV DORQJ WKH FUDFN IURQW ZHUH XVHG IRU WKH
EHWZHHQ WKH ILQH PHVK QHDU WKH FUDFN WLS DQG WKH

E\ IRXU ULQJV RI HOHPHQWV DQG HDFK ULQJ FRQWDLQV ... ILQLWH HOHPHQW PHVK DW WKH FKRUG FURZQ SRVLWLRQ



)LJXUH &ORVH XS 9LHZ RI)LQLWH (OHPHQW 0RGHO DW &URZQ SRVLWLRQ

675(66 ,17(16,7<)$&725 &$/&8/$7,21

*HQHUDO 0HWKRGRORJ\

)URP WKH NQRZOHGJH RI OLQHDU HODVWLF IUDFWXUH PHFKDQLFV ... VWUHVV LQWHQVLW\ IDFWRUV FDQ EH H[SUHVVHG DV IROORZV

u = $\frac{K_I}{G}\sqrt{\frac{r}{Œ}}$ > N FRV $\frac{\theta}{}$ FRV $\frac{\theta}{}$ FRV @

$\frac{K_{II}}{G}\sqrt{\frac{r}{Œ}}$ > N $\frac{\theta}{}$ VLQ $\frac{\theta}{}$ r VLQ @ R

v = $\frac{K_I}{G}\sqrt{\frac{r}{Œ}}$ > N VLQ $\frac{\theta}{}$ VLQ $\frac{\theta}{}$ VLQ @

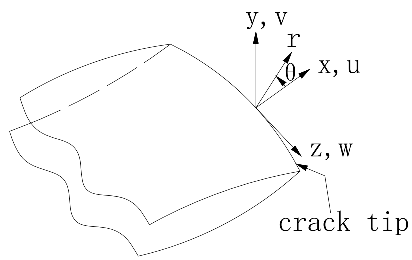
$\frac{K_{II}}{G}\sqrt{\frac{r}{Œ}}$ > N $\frac{\theta}{}$ FRV $\frac{\theta}{}$ r FRV @ R

w = $\frac{K_{III}}{G}\sqrt{\frac{r}{Œ}}$ VLQ $\frac{\theta}{}$ r R

ZKHUH

N = $-\nu$ plane strain; $\frac{3\nu}{1+\nu}$ plane stress

,Q (T u v w GHQRWHV WKH ORFDO UDGLDO ... QRUPDO ... WDQJHQWLDO ... K_{III} DUH WKH PRGH , ,, ,,, VWUHVV LQWHQVLW\ IDFWRUV ... GHQRWHV WKH 3RLVVRQ¶V UDWLR

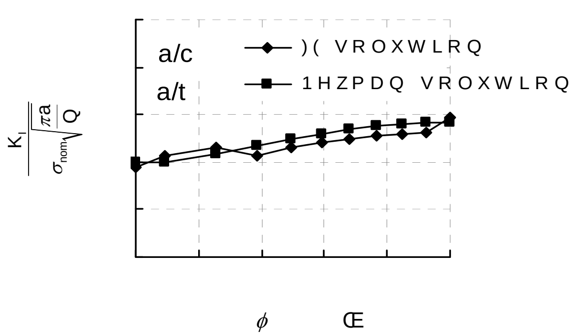


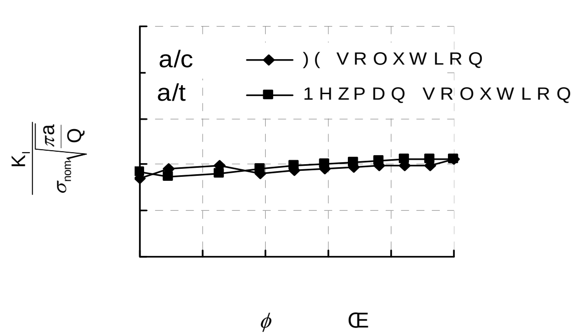
)LJXUH &UDFN 7LS &RRUGLQDWH 6\VWHP

%DVHG RQ WKHVH HTXDWLRQV GLVSODFHPHQW FRPSRQHQWV QHDU WKH FUDFN
WKH VWUHVV LQWHQVLW\ IDFWRU ...
WKH FUDFN PHHWV WKH ZHOG $ ...
VWDWH DUH JUHDWHU WKDQ WKRVH ...
YDOXH 3ODQH VWUDLQ VWDWH ZDV ...
DQG VLPSOLFLW\ SODQH VWUDLQ DVVXPSWLRQ LV DGRSWHG ...

9HULILFDWLRQ ZLWK)ODW 3ODWH

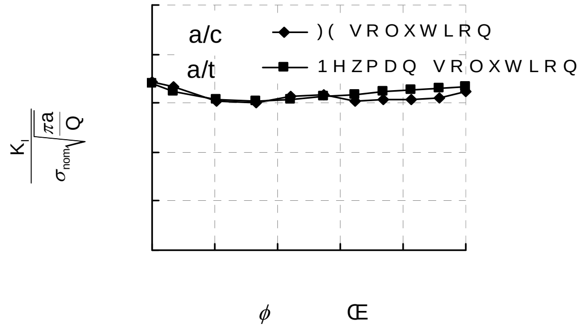
7R YDOLGDWH WKH $3'/ SURJUDPV ...
IDFWRUV IRU D VLPSOH ...
ZLGHO\ DFFHSWHG UHVXOWV JLYHQ E\ 1HZPDQ ...
PRGHO LV FRQVLVWHQW ZLWK WKH ...
ZLGWK DQG WKLFNQHVV RI PP ...
ZHUH FRQVLGHUHG WKH ILUVW ...
WKH RWKHU RQH LV EHQGLQJ PRPHQW ...
IROORZLQJ FUDFN VL]HV DUH FRQVLGHUHG LQ WKH YDOLGDWLRQ ...
7KH FRPSXWDWLRQ ...
FDQ EH QHJOHFWHG σ_{QRP} ...
FRPSDUHG ZLWK WKH 1HZPDQ 5DMX¶V ...
FUDFNV VHH)LJXUH ,W FDQ ...
RWKHU σ_{QRP} ZKHUH WKH QRPLQDO ...
1HZPDQ 5DMX¶V VROXWLRQ 7KH PD[LPXP ...
WKH GHHSHVW SRLQW DQG ...
6,) UHVXOWV LQ WKH FDVH RI D IODW SODWH ZLWK VXUIDFH F...

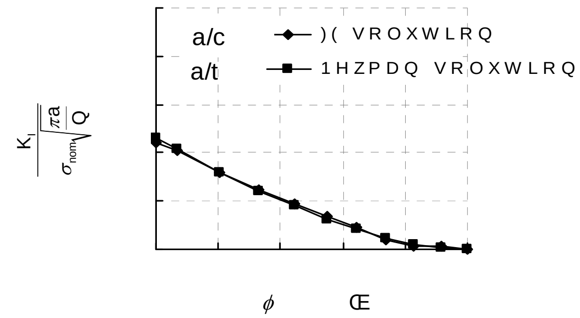




D)ODW SODWH LQ WHQVLRQ ... EHQGLQJ PRP...

)LJXUH 'LVWULEXWLRQ RI D)ODW 3ODWH ZLWK 6KD...



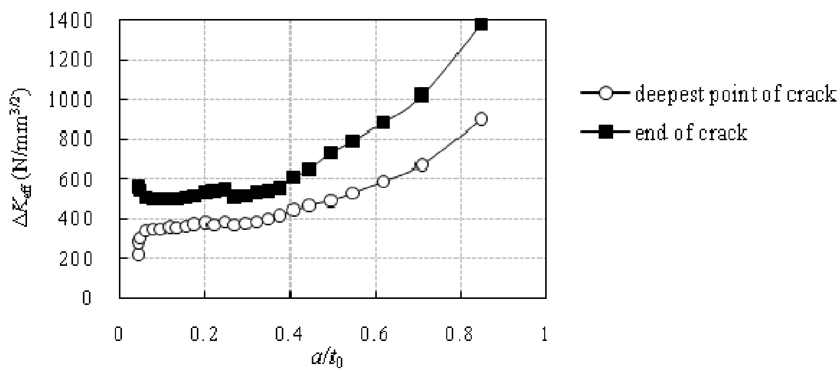


D)ODW SODWH LQ WHQVLRQ SXUH EHQGLQJ PRPHQ
)LJXUH 'LVWULEXWLRQ RI D)ODW 3ODWH ZLWK 'H

&DOFXODWLQJ 6,)V IRU :HOGHG &)&+6 7 MRLQW

$IWHU WKH ILQLWH HOHPHQW PRGHO FDVVH DW WKH WHG LQ DQDO
WKH ZHOGHG &)&+6 7 MRLQWV ZLWK VXUIDFH LQLWLDO FUDFNV
6SHFLPHQ &)&+6 7 MRLQW LQ WKH KRW VSRW\ VWUHVV GLVWULEXWLRQ
7RQJML 8QLYHUVLW\ LV VHOHFWHG IRU WKH VWXG\ 7KH GLPHQVLRQ
WKLV 7 MRLQW VSHFLPHQ DUH PP FRQFUHWH JUDGH LV
VWHHO PDWHULDO LV 4 FU RQ D [L DO FRPSUHVVLRQ WR WKH EUD
7 MRLQW 7KH FDOFXODWLRQ VKRZV WKDW WKH RUGHU RI PDJQL
WKHP LV WKXV QHJOLJLEOH ZKLFK LV FRQVLGHUHG LQ WKH
HIIHFWLYH VWUHVV LQWHQVLW\ IDFWRU ZKLFK FDQ EH FRPSX
DV JLYHQ LQ %6 >K@ DQG WKH VXEVFULSW HII LV XVHG WR GHQRWH WKH
LQWHQVLW\ IDFWRU RI WKH GHHSHVW SRLQW DQG FUDFN HQGV KDYH EHHQ
IRU GLIIHUHQW FUDFN VL]HV DV SUHVHQWHG LQ)LJXUH

$$K_{HII} = \sqrt{K_{,}^2 + K_{,,}^2 + K_{,,,}^2 / (1-\nu^2)}$$



)LJXUH 9DULDWLRQ RI (IIHFWLYH 6WUHVV ,QWHQ
DW WKH 'HHSHVW 3RLQW DQG &UDFN (QGV GXULQJ

)$7,*8(/,)(02'(/,1* $1' 35(',&7,21

$FFXUDWH IDWLJXH OLIH SUHGLFWLRQ GHSHQGV QRW RQO\ RQ WKH
VROXWLRQ EXW DOVR RQ WKH DSSURSULDWH FUDFN JURZWK

)DWLJXH *URZWK 0RGHO

3DULV¶ /DZ ZKLFK LV WKH PRVW SRSXODU IDWLJXH FUDFN EJ
(UGRJDQ > @ UHODWHV WKH IDWLJXH FUDFN JURZWK UDWH J
(T EHORZ

$$\frac{@a}{@N} \quad \& K\hat{u}^{P}$$

ZKHUH LV WKH QXPEHU RI WKH ORDG F\FOHV ûK LV WKH VWUHVV LQWHQVLW\
DQG P DUH WKH FUDFN JURZWK PDWHULDO FRQVWDQWV RI WKH
E\ LQWHJUDWLQJ (T LI WKH VWUHVV LQWHQVLW\ UDQJH LV
ILQDO FUDFN GHSWK a_I ZKHQ L H

$$\int^{1} NG \int_{a}^{a_I} \frac{@a}{\& K\hat{u}^{P}}$$

+RZHYHU GLIILFXOW\ H[LVWV LQ REWDLQLQJ WKH VROXWLRQ
RFFXUV ZLWK JURZLQJ FUDFN VL]H
3DULV /DZ LV H[SUHVVHG LQ DQ RUGLQDU\ GLIIHUHQWLDO
(XOHU PHWKRG FDQ EH XVHG WR FRQYHUW (T LQWR

$$N_Q \quad N_Q \frac{@a}{\& K\hat{u}_Q^{P}} \quad Q \quad W$$

ZKHUH LV WKH QXPEHU RI LQWHJUDWLRQ WLPH LQWHUYDO
3' > @ &L H× ⁻ DQG P

&UDFN 6KDSH $VVXPSWLRQ

7KH 1HZPDQ DQG 5DMX¶V ³7ZR SRLQW PHWKRG´
UHODWLRQVKLS RI WKH FUDFN¶V DVSHFW UDWLR
WKLV VWXG\ DQG WKH FUDFN JURZWK

$$\begin{cases} \frac{@a}{@N} \quad \& K_{\$}\hat{u}^{P} \quad D \\ \frac{@c}{@N} \quad \& K_{\&}\hat{u}^{P} \quad F \end{cases}$$

ZKHUH ûK_D DQG ûK_F GHQRWH WKH VWUHVV LQWHQVLW\
UHVSHFWLYHO\
UHODWLRQV KDYH EHHQ SURSRVHG & IRU
DGRSWHG VLQFH LW LV PRUH FRQVHUYDWLYH

$$\begin{cases} a_Q \quad a_Q \; N \quad K\hat{u}_D{}^{P}{}_{HII} > \; \& \quad \hat{u} \quad @ \\ c_Q \quad c_Q \; N \quad K\hat{u}_F{}^{P}{}_{HII} > \; \& \quad \hat{u} \quad @ \end{cases}$$

)DLOXUH &ULWHULRQ DQG)DWLJXH /LIH (VWLPDWLRQ

7KH FULWLFDO FUDFN VL]H LV GHILQHG DV WKH FUDFN VL]H DW
DVVXPHG WR RFFXU)RU WKH IDWLJXH OLIH HVWLPDWLRQ
GHWHUPLQHG HLWKHU DV D FULWLFDO OHQJWK RU
DYDLODEOH IRU ZHOGHG &)&+6 MRLQWV
KROORZ VHFWLRQ MRLQWV PLJKW SHUIRUP
ZHOGHG &)&+6 7 MRLQWV LQ WKH SUHVHQW
XVHG E\ 6FKXPDFKHU HW DO > @ WKH FULWLFDO
1XVVEDXPHU > @ DQG 1XVVEDXPHU DQG +DOO
FRPPRQO\ DFFHSWHG DV WKH FULWLFDO
GLUHFWLRQ ZKHQ WKH FUDFN SHQHWUDWHV
IDWLJXH OLIH DV WKH PDMRULW\ RI WKH OLIH LV VSHQW DW V

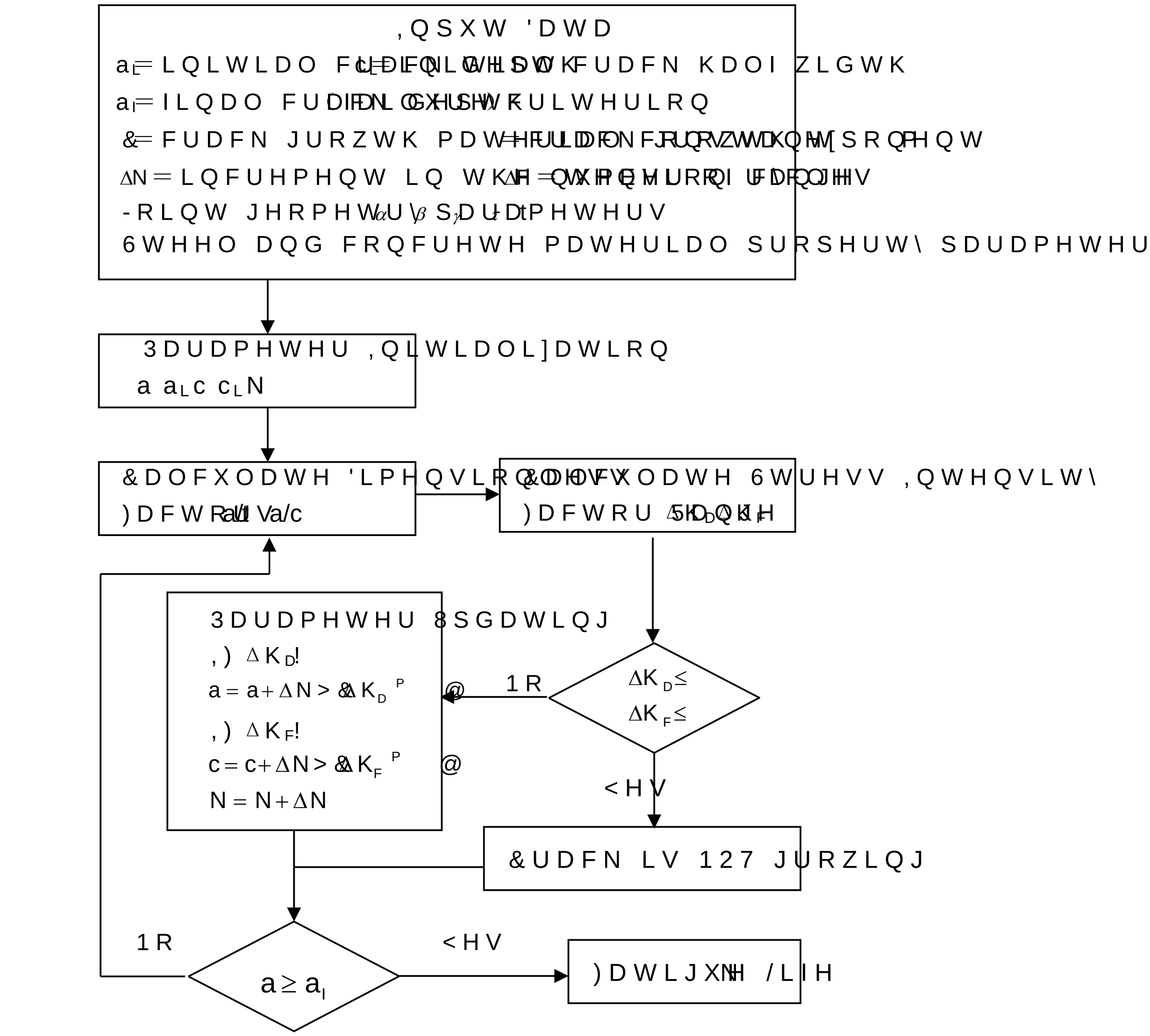
7R DYRLG XQH[SHFWHG IDLOXUH
VHUYLFHDELOLW\ FULWHULRQ
WDNHQ DV WKH FULWLFDO FUDFN VL]H

7KH IDWLJXH WHVW UHVXOWV RI WKH
VKRZ WKDW WKH ORDG F\FOHV
WKURXJK WKH ZDOO WKLFNQHVV RI
FDSDFLW\ GLIIHU IURP HDFK RWKHU
WHUPLQDWHG ZKHQ WKH FUDFN GHSWK

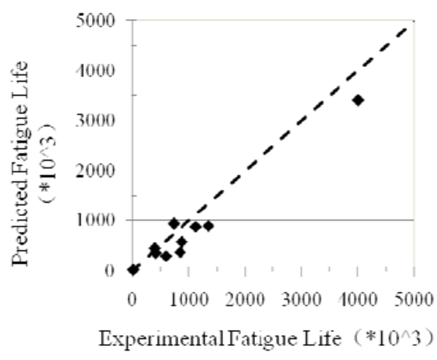
5HVXOWV DQG 'LVFXVVLRQV

)ROORZLQJ WKH DIRUHPHQWLRQHG
F\FOLF WHQVLRQ ORDG LQ LWV EUDFH
WR LPSOHPHQW WKLV SURFHGXUH LQ
7DEOH L ZLWK PP DQG PP ZDV OLVWHG WR LOOXVWUDWH WKH
GLYLGHG LQWR D WRWDO RI VWDJHV

7R HYDOXDWH WKH YDOLGLW\ RI
7 MRLQWV ZHUH SUHGLFWHG DQG FRPSDUHG
)LJXUH ,W FDQ EH VHHQ IURP)LJXUH
WKH H[SHULPHQWDO GDWD 7KH
)(UHVXOWV DQG H[SHULPHQWDO
ZDV XVHG KHUH ZKLFK PLJKW EH
DQG P SDUDPHWHUV VHW E\ WKH 3'(> @
XVHG WR DSSUR[LPDWH WKH IDWLJXH
ZHOGLQJ SURFHVV ZDV QRW WDNHQ
GHWHUPLQHG IDWLJXH OLIH PLJKW
WKH IXOO FKRUG WXEH WKLFNQHVV
GLUHFWLRQ



)LJXUH)ORZ &KDUW (VWLPDWLRQ 6R7)DWLJXH /LIH 0HWKRGV &)&+



)LJXUH &RPSDULVRQ EHWZHHQ 3UHGLFWHG DQG ([SH

7DEOH ,OOXVWUDWLYH ([DPSOH IRU &+6)DWLJXH /LIH (VW

VWHS	a PP	c PP	△K_D 1 PP	△K_F (1 PP)	△N î	N î	a PP	c PP

7DEOH &RQSDULVRQ LQ)DWLJXH /LIH EHWZHHQ)(

-RLQW	)(SUHGLFWHG IDWLJXH OLIH	([SHULPHQWDO IDWLJXH OLIH
&)&+6		
&)&+6		
&)&+6		
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&)&+6		
&)&+6		
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&)&+6		

5.4.1 Effect of initial crack size

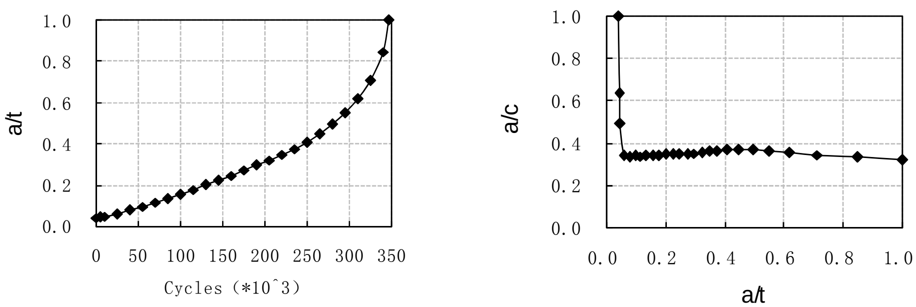
7KH GDWD SUHVHQWHG LQ 7DEOH VLV]H a_i c_i VHG RQ PDVV,XPHG IRU LQWHUHVW WR VWXG\ WKH HIIHFW RI LQLWLDO FUDFN VL]H FDVHV ZLWK LQFUHDVLQJ a_i LQLWLDO FUDFN VL]H a_i c_i PP ZKLFK IDOO ZLWKLQ WKH V6(1 DJ LQ WKH UXOH SDUDPHWULF VWXG\ RI WKH &)&+6 WKH ORQJHU WKH IDWLJXH OLIH WKH EHQFKPDUN FDVH PHW LV IRXQG WKDW WKH IDWLJXH 7 MRLQWV ZLWK QRUPDO TXDOLW\ GR QRW FKDQJH PRUH WKDQ

7DEOH (IIHFW RI ,QLWLDO &UDFN 6L]H RQ)DWLJXH

1R	,QLWLDO FUDFN VL]H 1L	)DWLJXH OLIH 1L 1
	aLcL PP	
	aLcL PP	
	aLcL PP	
	aLcL PP	
	aLcL PP	

5.4.2 Crack growth behavior

)LJXUH VKRZV WKH UHODWLRQVKLS EHWZHHQ FUDFN VL]H DQG F\FOHV DQG WKH UHVXOWV &)&+6 7 VSHFLPHQ ZKLOH RWKHU VSHFLPHQV KDYH VLPLODU WUHQG IDWLJXH OLIH LV LQ WKH VKDOORZ FUDFN VWDJH DQG WKH FUDFN JURZWK GHSWK GLUHFWLRQ ZKLOH SURSDJDWLRQ UDWH LQFUHDVHV ZKHQ D F UDWLR GURSSHG IURP WR NDV FUDFN GHSWK UHDFKHG KDOI ZDOO WKLFNQHVV EUHDFK JURZWK REVHUYDWLRQ DJUHHV ZHOO ZLWK WKH H[SHULPHQW WR ODUJH FUDFN VSUHDG RYHU WKH FUDFN YLVLEOH UHWURILW DFWLRQV VXFK DV ORFDWLRQ RQ WKH &)&+6 VWUXFWXUH XQGHU IDWLJXH ORDGLQJ



D &\FOH UHODWLRQ FXUYH a/t E a/t a/c UHODWLRQ FXUYH

)LJXUH 5HODWLRQVKLS EHWZHHQ &UDFN 6L]H DQ

5.4.3 Effect of concrete grade

&)&+6 &)&+6 DQG &)&+6 7 MRLQWV KDYH GLIIHUHQW JHRPHWULFDO β O γ SDUDPHWHUV EXW GLIIHUHQW FRQFUHWH JUDGHV 7DEOH ,W FDQ EH VHHQ IURP 7DEOH WKDW DV FRQFUHWH JUDGH LQFUHDVHV WKUHH &)&+6 7 MRLQWV FRQFUHWH GHFUHDVHV DV FRQFUHWH JUDGH H[DPSOH IRU D 7 MRLQW KDYLQJ WKH VDPH &)&+6 FRQFUHWH JUDGHV IURP & WR & FRQFUHWH JUDGH LQFUHDVHV EXW FRQFUHWH ILOOHG WXEXODU VWUXFWXUHV LPSURYHPHQW LQ IDWLJXH EHKDYLRU WKH ULJLGLW\ QRW VWUHQJWK GHFUHDVHV KRW VSRW VWUHVV FRQFHQWUDWLRQ

7DEOH (IIHFW RI &RQFUHWH 7*UDGH RQ 6&)$_{PD[}$

-RLQW	&)&+6	&)&+6	&)&+6
&RQFUHWH JUDGH	&	&	&
6&)$_{PD[}$			
6&)$_{PD[}$ UDWLR WR &			

7DEOH (IIHFW RI &RQFUHWH)*UDGH RQ 6&)$_{PD[}$

&RQFUHWH JUDGH	&	&	&	&	&	&	&
6&)$_{PD[}$							
6&)$_{PD[}$ UDWLR WR &							

&21&/86,216

7KLV SDSHU RXWOLQHV D IDWLJXH GHVLJQ FRQVLGHUHG DSSURDFK ... VHFWLRQ &)&+6 7 MRLQW VXEMHFWHG ... SHUIRUPHG WR FRPSXWH WKH VWUHVV &RQFHQWUDWLRQ ... SURJUDPV ZHUH GHYHORSHG LQ WKH $16<6 ... WLS VLQJXODU HOHPHQW LV FRQVWUXFWHG ... SUHVHQWHG DQG FRPSDUHG ZLWK WKH VKRUWHVW ... DQDO\VLV DSSURDFK IRU IDWLJXH OLIH ... FRQFOXVLRQV FDQ EH GUDZQ EDVHG RQ WKH ILQGLQJV RI WKL

%DVHG RQ H[SHULPHQWDO GDWD RI ... PRGHO IRU FDOFXODWLQJ WKH VWUHVV ... HVWDEOLVKHG

,Q RUGHU WR REWDLQ FRQYHUJHG ... WKH VWHHO WXEH DQG WKH H[WHUQDO ... EH VHSDUDWHG HYHQ WKRXJK WKH\ ... EHWZHHQ WKH LQWHUIDFH QRGHV ...

$ IDWLJXH OLIH HVWLPDWLRQ ... OLIH HVWLPDWHG IURP ILQLWH HOHPHQW ... UHVXOWV 7KH HIIHFW RI WKH ... LQ IDWLJXH OLIH RI ZHOGHG &)&+6 ... IDOOLQJ ZLWKLQ WKH UDQJH VSHFLILHG E\ +6(ZDV ZLWK

5HODWLRQVKLS EHWZHHQ WKH FUDFN ... 7 MRLQWV 7KH PRVW SDUW RI ... VWDJH ,Q VKDOORZ FUDFN VWDJH ... SURSDJDWHV PRUH UDSLGO\ DORQJ ... WKLFNQHVV FUDFN ... H[WHUQDO UHLQIRUFLQJ QHHG ... UHJLRQ RI WKH &)&+6 VWUXFWXUH VXEMHFWHG WR F\FOL

7KH ILOOHG LQ FRQFUHWH FDQ ... MRLQW 7KLV EHKDYLRU EHQHILWV ... ULJLGLW\ GLVWULEXWLRQ RI WKH ... FRQFHQWUDWLRQ DW WKH ZHOG ... LWVHOI KDV QR VLJQLILFDQW LQIOXHQFH RQ VWUHVV FRQ

$&.12:/('*(0(176

7KH DXWKRUV ZRXOG OLNH WR DFNPQWRKHGDWXWKH 6FLQDHQFHDQG
RI &KLQD WKURXJK WKH JUDQWV 12 K DXWKDRUG LV DOVR7KDHDW
.ZDQJ +XD 6FKRODU)RXQGDWLRQ RI DRQ1WLRQDOHUQDWFLRO
WKLV UHVHDUFK SURMHFW

127$7,21

a 'HSWK RI D VHPL HOOLSWLFDO FUDFN
a 'HSWK RI D LQLWLDO FUDFN
aI 'HSWK RI D ILQDO FUDFN
c +DOI OHQJWK RI D VHPL HOOLSWLFDO FU
L /HQJWK RI D FKRUG
L /HQJWK RI D EUDFH
d ([WHUQDO GLDPHWHU RI D FKRUG
d ([WHUQDO GLDPHWHU RI D EUDFH
t :DOO WKLFNQHVV RI D FKRUG
t :DOO WKLFNQHVV RI D EUDFH
α &KRUG OHQJWK SDUDPHWHU
β 'LDPHWHU UDWLR EHWZHHQ D EUDFH DQG D FKRUG
γ +DOI GLDPHWHU WR WKLFNQHVV UDWLR RI D FKRUG
τ :DOO WKLFNQHVV UDWLR EHWZHHQ D EUDFH DQG D FKRU
hf +HLJKW RI ZHOG WRH RQ WKH FKRUG VLGH
hf +HLJKW RI ZHOG WRH RQ WKH EUDFH VLGH
c 2XWHU FLUFXPIHUHQFH RI D FKRUG
c ,QQHU FLUFXPIHUHQFH RI D FKRUG
c 2XWHU FLUFXPIHUHQFH RI D EUDFH
c ,QQHU FLUFXPIHUHQFH RI D EUDFH
c 3URMHFWHG OHQJWK LQ SODQH RI ZHOG WRH RQ WKH FK
K 6WUHVV LQWHQVLW\ IDFWRU
K, 6WUHVV LQWHQVLW\ IDFWRU RI 0RGH ,
K,, 6WUHVV LQWHQVLW\ IDFWRU RI 0RGH ,,
K,,, 6WUHVV LQWHQVLW\ IDFWRU RI 0RGH ,,,
ûK 6WUHVV LQWHQVLW\ IDFWRU UDQJH
KHII (IIHFWLYH VWUHVV LQWHQVLW\ IDFWRU
γθ 3RODU FR RUGLQDWH V\VWHP IRU D FUDFN WLS
* (ODVWLF VKHDU PRGXOXV
ν 3RLVVRQ¶V UDWLR
uvw /RFDO UDGLDO QRUPDO DQG WDQJHQWLDO GLVSODFHPH
& 3DULV¶V FUDFN JURZWK ODZ FRHIILFLHQW
P 3DULV¶V FUDFN JURZWK ODZ H[SRQHQW
N 1XPEHU RI F\FOHV
σQRP 1RPLQDO VWUHVV LQ D SODWH
Q 6KDSH IDFWRU LQ 1HZPDQ 5DMX¶V VROXWLRQ
6&) 6WUHVV FRQFHQWUDWLRQ IDFWRU

5()(5(1&(6

> @ :DUGHQLHU - 3DFNHU -$ =KDR ³,+ /RDGLQJ RI 6WHHO 7XEXODU -RLQWV
6WUXFWXUDO $SSOLFDWLRQV´ 'HOIW %RXZHQ PHW 6WDDO
> @ =KDR ; / +DQ / + DQG /X + 0HPEHU FDSDFLW\ RI FROG IRUPHG...
/RQGRQ 7D\ORU)UDQFLV SS
> @ =KDR ; / +HULRQ 6 3DFNHU -$ ...
YDQ :LQJHUGH $ 0 DQG <HRPDQV 1 ...
6HFWLRQ :HOGHG -RLQWV XQGHU)DWLJXH /RDGLQJ´ &,'(&7
> @ /HH & &KLHZ 6 /LH 6 DQG 6RK ...
7 MRLQW ZLWK &RXPSHULU ...
9RO 1R SS
> @ /HH & . &KLHZ 6 3 DQG /LH 6 7 ...
)DFWRUV IRU 3DUWLDOO\ 2YHUODSSHG ...
&RQVWUXFWLRQ 9RO 1R SS
> @ YDQ :LQJHUGH $ 0 3DFNHU - $ ...
,,: ,QWHUQDWLRQDO &RQIHUHQFH RQ ...
6DQ)UDQFLVFR 86$ SS
> @ 7RQJ / DQG ; / =KDR HW DO ...
&LUFXODU DQG 6TXDUH +ROORZ 6HFWLRQ ...
1R SS
> @ 8GRPZRUDUDW 3 0LNL & ...
7 ³)DWLJXH DQG ...
-RXUQDO RI 6WUXFWXUDO (QJLQHHULQJ 9RO $ SS
> @ 7RQJ / : 6XQ & 4 &KHQ < ...
&RPSDULVRQ LQ +RW 6SRW 6WUHVV ...
WK ,QWHUQDWLRQDO 6\PSRVLXP ...
> @ 0DVKLUL) 5 DQG =KDR ; / ...
VXEMHFWHG WR LQ SODQH)DWLJXH ...
1R SS
> @ =KDR ; / DQG 7RQJ / : ³1HZ 'HYHORSPHQWV ...
6WUXFWXUDO (QJLQHHULQJ 9RO 1R SS
> @ :DQJ . 7RQJ / : =KX - ...
RI :HOGHG 7 MRLQWV EHWZHHQ &+6 ...
%UDFH´ -RXUQDO RI %ULGJH (QJLQHHULQJ 9RO 1R
> @ +REEDFKHU $ ³6WUHVV ,QWHQVLW\ ...
9RO 1R SS
> @ %RZQHVV ' DQG /HH 0 0 . ³7KH ...
$VVHVVPHQW RI 'RXEO\ &XUYHG &UDFN ...
9RO 1R SS
> @ $PHULFDQ :HOGLQJ 6RFLHW\ $:6 ...
SS
> @ +HDOWK DQG 6DIHW\ ([HFXWLYH ...
DQG &RQQHFWLRQV LQ 2IIVKRUH 6WUXFWXUHV´ 2 7HFK
> @ $16<6 5HOHDVH +HOS 6\VWHP ...
> @ %DUVRXP 5 6 ³7ULDQJXODU ...
(OHPHQWV´ ,QW - 1XP 0HWK (QJ 9RO 1R SS

> @ &KLHZ 6 3 /LH 6 7 /HH &V.V ,QWGHQ+VLWDQ\J)D=FWRU ³6WUHVV
&UDFN LQ D 7XEXODU 7 MRLQW´ 9HWVHHQVWDLQRGQ3DOSHRXUQDO
1R SS
> @ %RZQHVV ' /HH 0 0 . ³$)LQVLW)HLH(OHPHQWG 6WXGHV RI
)DFWRUV LQ 7XEXODU -RLQWV´ -RXUQDO 1RI 6WSUDLQ $QDO\
> @ 1HZPDQ - & DQG 5DMX , 6 W³$\)QDFWRU (FDO 6WUHVV ,QW
&UDFN´ (QJLQHHULQJ)UDFWXUH 0HFKDQLFV 9RO 1
> @ %ULWLVK 6WDQGDUGV ,QVWLWXWLRQ 3XEOLVKHG %6 LQJ WKH $FFHSWDQFH
)ODZV LQ 0HWDOOLF 6WUXFWXUHV´ /RQGRQ 8. SS
> @ 3DULV 3 & ³&ULWLFDO $QDO\VLV RI &UDFN 3URSDJDWLRQ´ -RXUQDO
%DVLF (QJLQHHULQJ 9RO 1R SS
> @ %ULWLVK 6WDQGDUGV ,QVWLWXWLRQ $VVHVVLQJ WKH $FFHSWDELOLW\
RI)ODZV LQ)XVLRQ :HOGHG 6WUXFWXUHV´ /RQGRQ 8.
> @ 6FKXPDFKHU $ DQG 1XVVEDXPHU $ ³([SHULPHQWDO %HK
:HOGHG 7XEXODU . MRLQWV IRU %ULGJH 'HVLJQ´ (QJLQHHULQJ 6
> @ %RUJHV / DQG 1XVVEDXPHU $ ³,QWHJUDWHG 1XPHULFDO
:HOGHG &+6 . MRLQWV´ 3URFHHGLQJV RI 7XEXODU 6WUXFWXUHV
&KLQD SS
> @ 1XVVEDXPHU $ DQG +DOGLPDQG 6WLIIQHVV 6X&LQJ)DWLJXH
RU &DVW 6WHHO 1RGH 6ROXWLRQV´ 3URFHHGLQJV RI 7XEXODU
6WUXFWXUHV /RQGRQ SS