Optimization Techniques for Non-Linear Systems Analysis

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Massachusetts Institute of Technology, Cambridge, USA

Abstract²2SHQJURXQGVWRUH\ZLWKIORDWLQJFROXPQV LVDW\SLFDO IHDWXUHLQWKHPRGHUQPXOWLVWRU\FRQVWUXFWLRQVLQXEDQ,QGLD6XFK IHDWXUHVDUHYHU\PXFKXQGHVLUDEOHLQEXLOGLQJ VEXLOWLQVHLVPLFDOO\ DFWLYH DUHDV 7KH SUHVHQW VWXG\ SURSRVHV D IHDVLEOH VROXWLRQ WR PLWLJDWH WKH HIIHFWV FDXVHG GXH WR QRQXQLIRUPLW\ RI VWLIIQHVV DQG GLVFRQWLQXLW\LQORDGSDWKDQGWRVLPXOWDQHRXVO\KROGWKHIXQFWLRQDO XVHRIWKHRSHQVWRUH\SDUWLFXODUO\XQGHUWKHIORDWLQJFROXPQWKURXJK D FRPELQDWLRQ RI YDULRXV ODWHUDO VWUHQJWKHQLQJ V\VWHPV $Q LQYHVWLJDWLRQLVSHUIRUPHGRQDQH[DMSOHEXLOGLQJZLWKQLQHGLIIHUHQW DQDO\WLFDO PRGHOV WR EULQJ RXW WKH LPSRUWDQFH RI UHFRJQLVLQJ WKH SUHVHQFHRIRSHQJURXQGVWRUH\DQGIORDWLQJFROXPQV7ZRVHSDUDWH DQDO\VHV RQ YDULRXV PRGHOV RI WKH EXLOGLQJ QDPHO\ WKHHTXLYDOHQW VWDWLFDQDO\VLVDQGWKHUHVSRQVHVSHFWUXPDQDO\VLVDSSURDFK ZHUH SHUIRUPHG 9DULRXV PHDVXUHV VXFK DV LQFRUSRUDWLRQ RI &KHYURQEUDFLJVDQGVKHDUZDOOVVWUHQJWKHQLQJWKHFROXPQVLQWKH RSHQJURXQGVWRUH\DQGWKHLUGLIIHUHQWFRPELQDWLRQ 7KHDQDO\VLVRQWKDWWZRVKRUWRQHVVHSDUDWHG E\ LQWHUFRQQHFWLQJ EHDPV WKH VWUXFWXUDO ZDOOV DUH PRVW HIIHFWLYH ZKHQSODFHGDWWKHSHULSKHU\RIWKHEXLOGLQJVDQ GXVHGDVRQHORQJ VWUXFWXUDOZDOO)XUWKHUWFDQEHVKRZQWKDW WKHIRUFHWUDQVIHUIURP IORDWLQJFROXPQVEHFRPHVOHVVKRUL]RQWDOZKHQ WKH&KHYURQ%UDFLQJV DUHSODFHGMXVWWEHORZWKHPWKHUHE\UHGXFLQJWK HVKHDUIRUFHVLQWKH EHDPVRQZKLFKWKHIORDWLQJFROXPQUHVWV

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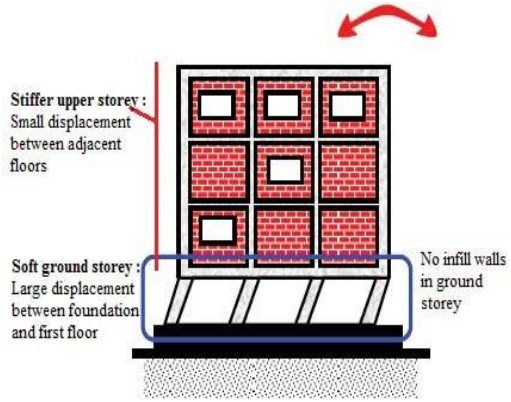

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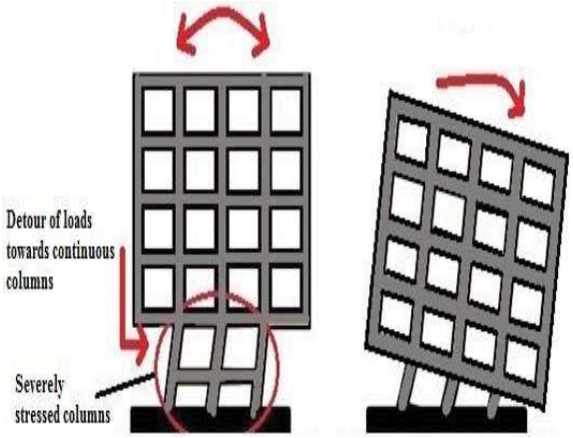

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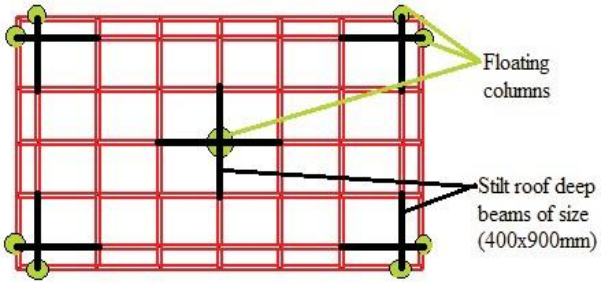

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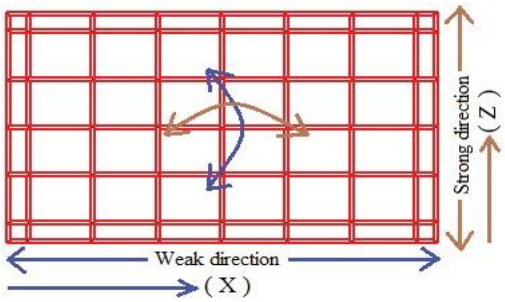

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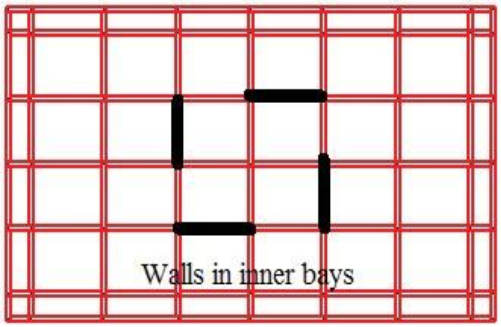

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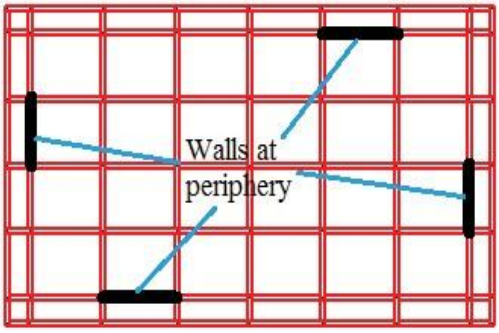

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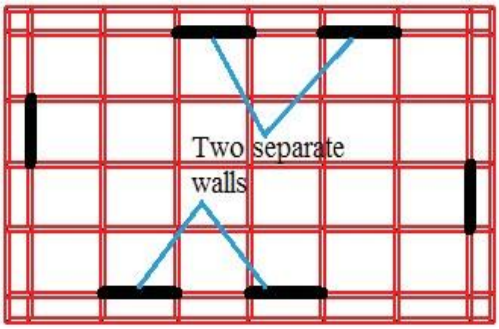

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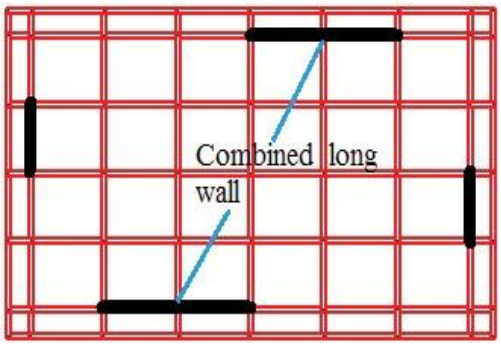

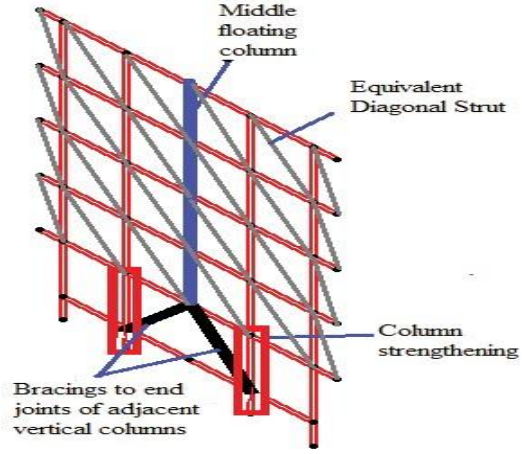

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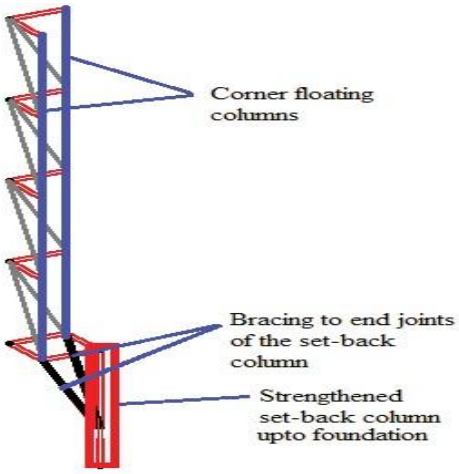

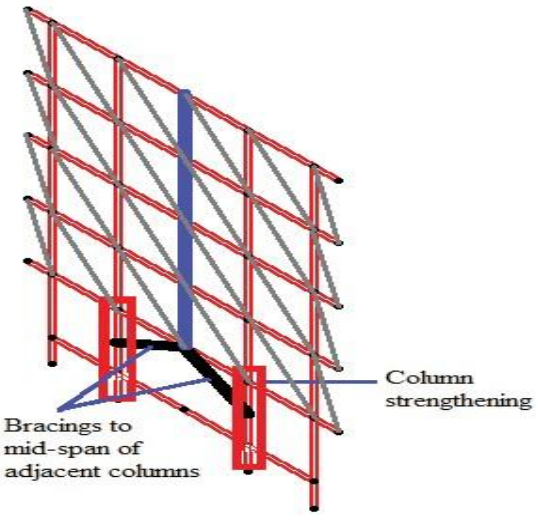

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A.Equivalent Static Analysis

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9E $K :

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B.Response Spectrum Analysis (Dynamic Analysis)

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A.Fundamental Periods

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6WDWLF '\QDPLF '\QDPLF 6WDWLF

B.Lateral Deformation

7KHODWHUDOGLVSODFHPHQWSURILOHVRIWKHY
DULRXVPRGHOVIRU
WKHWZRGLIIHUHQWDQDO\VHVSHUIRUPHGLQWKLV
VWXG\DUHVKRZQ
LQ)LJ,QWKHVHILJXUHVWKHDEUXSWFKDQJHVLQWK
HVORSHRI WKH SURILOH VWLSXODWH WKH
VWLIIQHVV LUUHJXODULW\ 7KH
GLVSODFHPHQWVDWJURXQGDQGILUVWIORRUOHYH
ODUHVKRZQLQ
7DEOHV,,DQG,,,WLVREVHUYHGWKDWWKHGLVSODF
HPHQWVDUH
UHGXFHGZKHQVKHDUZDOOVDUHLQWURGXFHG0RG
HODQG

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'LVSODFHPHQWPP		
0RGHO	;'LUHFWLRQ	='LUHFWLRQ
*URXQG)ORRU)LUVW)ORRU	*URXQG)ORRU	)LUVW)ORRU

:KHQ0RGHOVDQGDUHFRPSDUHGLWLVREVHUYHG
WKDWWKH
ODWHUDOGLVSODFHPHQWRIWKHEXLOGLQJLQWKH;
GLUHFWLRQKDV
EHHQFRQVLGHUDEO\GHFUHDVHGLQ0RGHO7KHEXL
OGLQJ0RGHOV
DQGKDYHVDPHWKHVL]HRIWKHVKHDUZDOOVEXWD
WVHSDUDWH
ORFDWLRQVLQWKH;GLUHFWLRQDWWKHSHULSKHU
\VXFKDVWZRVKRUW
VKHDUZDOOV)LJDQGRQHFRPELQHGORQJVKHDUZDO
O)LJ
UHVSHFWLYHO\6LQFHWKHFRQFHUQHGZDOODUHDL
VQRQHWKHOHVV
WKHVDPHLQERWKEXLOGLQJVEXWWKHEXLOGLQJZ
LWKORQJHUVKHDU
ZDOOVPRUHXQ\LHOGLQJWKDQWKRWKHUVDQGW
KXVDOORZVWKH
EXLOGLQJWREHPRUHHVLVWDQWDJDLQVWWKHO
DWHUDOPRWLRQDQG
KHQFHWKHODWHUDOGHIRUPDWLRQKDVEHHQWUH
PHQGRXVO\UHGXFHG
E\SURSHU\XVLQJWKHGRXEOHHQJWKVKHDUZDO
OV7KHUHIRUHLW
LVEHQHILFLDOWRNHHSRQHORQJVKHDUZDOOLQVW
HDGRIWKHWZR
VKRUWZDOOVKDYLQJVHSDUDWHGE\WKHLQWHU
HODWHGEHDPV
)XUWKHUPLWLVVHQWKDWWKHODWHUDOGHIRUPD
WLRQLVDOVR
UHGXFHGZKHQWKH&KHYURQ%UDFLQJVDUHLQFRU
SRUDWHGXQGHU
WKHIORDWLQJFROXPQLQWKHVWUHQJWKHQHGFRO
XPQVRIVWVWRUH\
RIWKHEXLOGLQJ0RGHODQG

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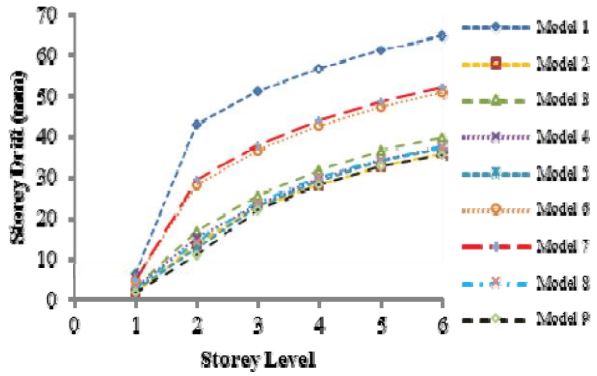
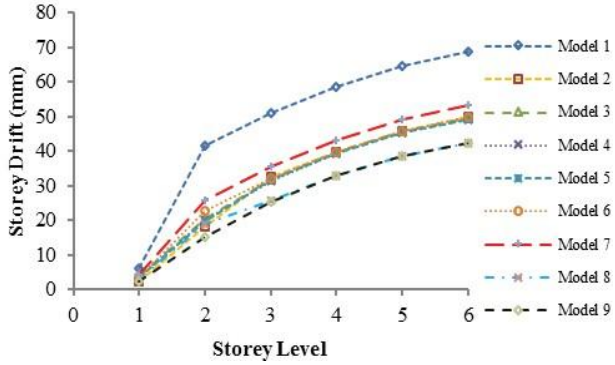
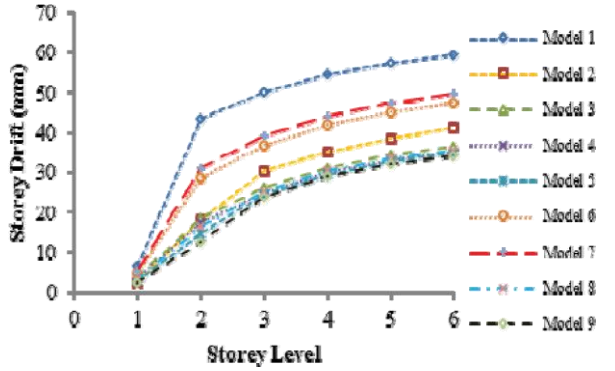
'LVSODFHPHQWPP		
0RGHO	;'LUHFWLRQ	='LUHFWLRQ
*URXQG)ORRU)LUVW)ORRU	*URXQG)ORRU	)LUVW)ORRU



)LJD/DWHUDOGLVSODFHPHQWSURILOHE\VWDWLF DQDO\VLVQ; GLUHFWLRQ



)LJE/DWHUDOGLVSODFHPHQWSURILOHE\VWDWLF DQDO\VLVQ= GLUHFWLRQ



)LJF/DWHUDOGLVSODFHPHQWSURILOHE\G\QDPLFDQDO\VLVQ; GLUHFWLRQ

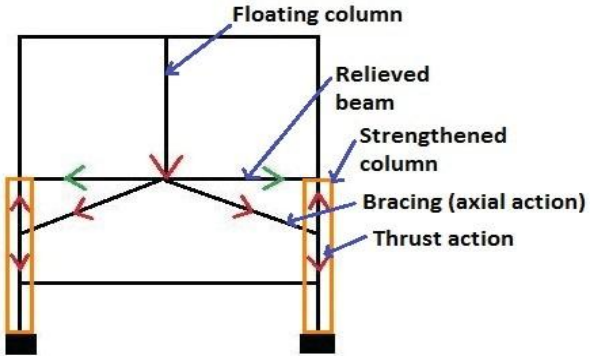
)LJG/DWHUDOGLVSODFHPHQWSURILOHE\G\QDPLFDQDO\VLVQ= GLUHFWLRQ

C.Shear Force in Beams on Which the Floating Columns Rest

)URP7DEOH,9DQG9LWLVFOHDUWKDWWKHVKHDUIRUFH GHPDQGVLQWKHEHDPVERWKWKHLQWHUPHGLDWH DQGRYHUKDQJRQ ZKLFKIORDWLQJFROXPQVUHVWVKDYHEHHQ[FHS WLRQDOO\UHGXFHG LQ0RGHO ,QWURGXFWLRQRIWKH&KHYURQEUDFLQJVLQWK HVRIWJURXQG VWRUH\KDVJUHDWO\KHOSHGLQJOREDOO\UHGXFLQ JWKHODWHUDO GHIRUPDWLRQRIEXLOGLQJ,Q0RGHOZLWKRXWWKHE UDFHVWKH WUDQVIHUIIRUFHVLVQRWYHUWLFDOZKLFKOHDG VWKEHDPVRQ ZKLFK WKH IORDWLQJ FROXPQV UHVW WR FDUU\ WKH IRUFHV KRUL]RQWDOO\ WR WKH FRQQLQXRXV FROXPQV DQG JHW KHDYLO\ VWUHVVHGLQVKHDU)LJ%XWDIWHUWKHLQJUHVVL RQRIWKH FKHYURQEUDFHVLQWKH0RGHOWKHWUDQVIHURIIRUFHVKDV EHFRPHOVVKRUL]RQWDO7KHIRUFHVKDYHEHHQW UDQVIHUUHGWR WKH EHDPV DQG WKH FROXPQV WKURXJK WKH EUDFH WKHUHE\ UHOLHYLQJWKHJLGHUEHDPVRQZKLFKWKHIORDW LQJFROXPQUHVWV 7KHUHIRUHIRUDVRIWJURXQGVWRUH\WKEUDFLQJ VVKRXOGEH NHSWLQUHOHYDQWED\VXQGHUWKHIORDWLQJFRO XPQVRDVWRUHGXFH WKHGLVFRQWLQXLW\LQWKHYHUWLFDOIORUFHVLQD EXLOGLQJ (YHQWKRXJKWKHODWHUDOGHIRUPDWLRQRIWK HEXLOGLQJDQG VKHDUIRUFHLQEHDPVRQZKLFKIORDWLQJFROXPQU HVWVLVOHVVLQ 0RGHOZKHQFRPSDUHGZLWKWKDWLQ0RGHOWKHOD WWHULV SUHIHUUHGVLWGRHVQRWFRPSOHWHO\RFFXS\WK HVSDFHXQGHUWKH IORDWLQJ FROXPQ DQG WKHUHE\ VLPXOWDQHRXVO\ KROGV WKH IXQFWLRQDOXVHRIWKHRSHQVWRUH\HVSHFLDOO\XQGHUWKHIORDWLQJ FROXPQV

7$%/(,9 ,17(50(',$7(%(0;,0806+($5.1

0RGHO	0D[LPXP6KHDUN1			
	6WDWLF$QDO\VLV		'\QDPLF$QDO\VLV	
	6+($5=	6+($5<	6+($5=	6+($5<



)LJ0RGHOD[LDODQGWKUXVWDFWLRQ

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29(5+$1*%($00$;,0806+($5.1

0RGHO	0D[LPXP6KHDUN1			
	6WDWLF$QDO\VLV		'\QDPLF$QDO\VLV	
	6+($5=	6+($5<	6+($5=	6+($5<

D.Maximum Forces in Ground Storey Columns (Braced Set-Back Columns and Braced Columns around Middle Floating Column)

7KHPD[LPXPEHQGLQJDQGVKHDUIRFHVLQWKHFROXPQV
EUDFHGERWKVHWEDFNDQGPLGGOHLQWKHJURXQGVWRUH\DUH
VKRZQLQ7DEOHV9,9,,9,,,,;,WLVVHHQWKDWWKHIRUFHVDUH
UHGXFHGLQWKHFROXPQVZKHQWKHVKHDUZDOOVDUHLQWURGXFHGLQ
WKHVRIWVWRUH\0RGHO7KHVHVKHDUZDOOVEHFDXVH
RIWKHLUKXJHLQLWLDOOODWHUDOVWLIIQHVVKHSLQUHGXFLQJWKHVKHDU
IRFHVDQGWKHEHQGLQJPRPHQWVLQWKHEHDPVDQGFROXPQV
ZKHQSURYLGHGDORQJZLWKWKHUHLQIRFHGFRQFUHWHPRPHQW
UHVLVWLQJIUDPHVDQGE\EHLQJWKHPRVWFUXFLDOSDUWRIODWHUDO
ORDGUHVLVWLQJ\VWHP7KH\KDYHDOVRLQGLUHFW\VXFFHHGHGLQ
ORQJFRPELQHGVWUXFWXUDOZDOOLQDSDUWLFXODUGLUHFWLRQV
UHGXFLQJWKHVWLIIQHVVLUUHJXODULW\LQWKHEXLOGLQJSODFHGDORQJZLWKWKHUDFHV
:KHQ0RGHOVDQGDUHFRPSDUHGERWKPRGHOVDUH
FRPELQDWLRQ RI DOO WKH ODWHUDO VWUHQJWKHQLQJ WHFKQLTXHV

7$%/(,;
%5$&('0,"/(&2/8010$;,0806+($5

0RGHO	6TXDUH &ROXPQ6L]H PP	0D[LPXP6KHDUN1			
		6WDWLF$QDO\VLV		'\QDPLF$QDO\VLV	
		6+($5=	6+($5<	6+($5=	6+($5<

GLVFXVVHG %RWK ODWHUDO VWUHQJWKHQLQJ
WHFKQLTXHV LH WKH
VWUXFWXUDORUVKHDUZDOOVDQGWKH&KHYURQEUDFHVXQGHUWKH
IORDWLQJFROXPQLQWKHVWUHQJWKHQHGFROXPQVDUHLQFRUSRUDWHG
LQWKHEXLOGLQJWRJHWWKHEHVWVWUXFWXUDOFRQILJXUDWLRQLQWHUPV RIVHLVPLFUHVLVWDQFH

TABLE VI
BRACED SET-BACK COLUMN MAXIMUM MOMENT

Model	Square Column Size (mm)	Maximum Moment (kNm)			
		Static Analysis		Dynamic Analysis	
		MOM-Z	MOM-Y	MOM-Z	MOM-Y
1	400	549.9	403.6	608.7	634.6
2	400	285.6	323.7	404.5	566.4
3	400	104.4	57.8	93.5	43.6
4	400	103.3	57.8	92.4	48.8
5	400	99.7	57.3	94.1	46.3
6	600	486.1	527.6	489	607.7
7	600	770.2	544.4	873.7	605.2
8	600	468.6	386.7	440.6	208.8
9	600	462.1	384.4	446.1	209.7

9,,&21&/86,21

TABLE VII
BRACED SET-BACK COLUMN MAXIMUM SHEAR

Model	Square Column Size (mm)	Maximum Shear (kN)			
		Static Analysis		Dynamic Analysis	
		SHEAR-Z	SHEAR-Y	SHEAR-Z	SHEAR-Y
1	400	212.7	264.6	366.3	287.7
2	400	172.2	136.2	333.8	192.4
3	400	14.6	38.1	34.6	34.2
4	400	14.3	37.8	34.7	33.9
5	400	14.4	35.9	34.1	32.6
6	600	271.7	220.2	306.6	296.4
7	600	350.2	843.4	838.1	923.8
8	600	187.9	320.7	263.5	300.8
9	600	186.0	310.2	255.7	291.2

TABLE VIII
BRACED MIDDLE COLUMN MAXIMUM MOMENT

Model	Square Column Size (mm)	Maximum Moment (kNm)			
		Static Analysis		Dynamic Analysis	
		MOM-Z	MOM-Y	MOM-Z	M
1	400	813.6	1247.1	818.3	1237.4
2	400	50.2	527.8	21.5	648.6
3	400	506.5	1163.7	593.8	1490.8
4	400	478.3	1132.5	584.9	1439.2
5	400	480.1	1128.3	583.1	1434.7
6	700	1313.4	304.6	1402.4	188.3
7	700	1418.8	1694.6	1544.6	1675.1
8	700	1058.9	1640.7	1256.7	1933.9
9	700	1011.2	1630.4	1230.1	1918.6

For severe requirements, combination Model 8 can be
5&IUDPHEXLOGLQJVZLWKRSHQJURXQGVWRUH\VDQGIORDWLQJ FROXPQV DUH NQRZQ WR SHUIRUP SRRUO\ GXULQJ VWURQJ
HDUWKTXDNHVKDNLQJ,QWKLVSDSHUWKHVHLVPLFFYXOQHUDELOLW\RI EXLOGLQJVZLWKVRIWJURXQGVWRUH\DQGIORDWLQJFROXPQVV VKRZQWKURXJKDQH[DPSOHEXLOGLQJ7KHODWHUDOGHIRUPDWLRQ DQGWKHVWUHQJWKGHPDQGVLQWKHJURXQGVWRUH\FROXPQVDUH YHU\ODUJHIRUEXLOGLQJVZLWKVRIWJURXQGVWRUH\V,WLVQRWHDV\

WRSURYLGHVXFKFDSDFLWLHVLQWKHFROXPQVRIWKHJURXQGVWRUH\ 7KXV LW LV FOHDU WKDW VXFK EXLOGLQJV ZLOO H[KLELW SRRU SHUIRUPDQFH GXULQJ D VWURQJ HDUWKTXDNH VKDNLQJ 7KLV GDQJHURXVIHDWXUHI,QGLDQ5&IUDPHEXLOGLQJVQHHGVWREH UHFRJQL]HGLPPHGLDWHO\DQGQHFHVVDU\PHDVXUHVQHHGWREH WDNHQWRLPSURYHWKHSHUIRUPDQFHRIWKHEXLOGLQJV 7KHVRIWJURXQGVWRUH\KDVEHFRPHDYHU\LPSRUWDQWDQG XVHIXOUHTXLUHPHQWRIDOPRVWHYHU\PXOWLVWRUH\EXLOGLQJLQ WKH XUEDQ FLWLHV DQG WKHUHIRUH FDQQRW EH H[WHUPLQDWHG 6RPHWLPHVWKHIORDWLQJFROXPQVDOVREHFRPHQFHFVVDU\WR KROGWKHSXUSRVHRIRSHQVSDFHVLQWKHJURXQGVWRUH\9DULRXV PHDVXUHVFDQKHOSLQRYHUFRPLQJWKHVHSFXOLDUVLWXDWLRQVRI DQRSHQJURXQGVWRUH\DORQJZLWKWKHIORDWLQJFROXPQVLQD EXLOGLQJ7KHXQGHUO\LQJSULQFLSOHRIDQ\VROXWLRQWRWKLV SUREOHPLVLQDUHGXFLQJWKHVWLIIQHVVLUUHJXODULW\LQWKHRSHQ JURXQGEUHGXFLQJWKHGLVFRQWLQXLW\LQORDGSDWKGXHWR

$20<
IORDWLQJFROXPQV7KHSRVVLEOHVFKHPHVWRDFKLHYHWK HDERYH

DUHLLQWURGXFWLRQRIVKHDUZDOOVDWSURSHUSRVLWLRQVLQWKH VRIWVWRUH\LLLQFRUSRUDWLRQRIODWHUDOEUDFLQJVXQG HUWKH IORDWLQJFROXPQWRWKHVWUHQJWKHQHGFROXPQVRIWKHV RIWVWRUH\ 7KHVHVFKHPHVKDYHEHHQIRXQGWRFRQVLGHUDEO\UHGXFH WKH ODWHUDOGULIWGHPDQGVDQGWKXVWKHVWUHVVUHVXOW DQWVRQWKH

JURXQGVWRUH\FROXPQVDQGWKEHDPVRQZKLFKIORDWLQ J FROXPQVUHVW$IHDVLEOHFRPELQDWLRQRIODWHUDOVWUH QJWKHQLQJ

WHFKQLTXHVLVSURSRVHGZKLFKQRWRQO\UHGXFHVWKHVWLIIQHVV LUUHJXODULW\\DQGGLVFRQWLQXLW\LQORDGSDWKEXWDOVRHWDLQVWKH IXQFWLRQDOUHTXLUHPHQWRIWKHRSHQJURXQGVWRUH\SDUWLFXODU\ XQGHUWKHIORDWLQJFROXPQV
SUHIHUUHGZKHUHDVLQJOHVWUXFWXUDOZDOOLQHDFK GLUHFWLRQV SODFHG DORQJ ZLWK WKH EUDFHV
0RUHRYHU IRU PRGHUDWH
UHTXLUHPHQWVFRPELQDWLRQ0RGHOFDQEHSUHIHUUHG ZKHUHD

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