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ABSTRACT

!ince the 8onan Point collapse in the 1K in 1*6/, the pro$ressi0e collapse anal,sis o residential '"ildin$s has $rad"all, dra9n the attention o ci0il en$ineers and the scienti ic comm"nit,. 8ecent ad0ances in comp"ter science and the de0elopment o ne9 n"merical methodolo$ies allo9 "s to per orm hi$h: idelit, collapse sim"lations. &his paper assesses di erent scenarios 9hich co"ld ha0e h,potheticall, ca"sed the collapse o the Champlain &o9er !o"th Condo in !"r side, Florida, in 2)21, one o the most catastrophic pro$ressi0e collapse e0ents e0er occ"rred. &he collapse anal,sis 9as per ormed "sin$ the latest de0elopments in the Applied %lement Method. A hi$h: idelit, n"merical model o the '"ildin$ 9as de0eloped accordin$ to the act"al str"ct"ral dra9in$s. !e0eral di erent collapse h,potheses 9ere e4amined, considerin$ 'oth col"mn ail"res and de$radation scenarios. &he anal,ses sho9ed that the ail"re o deep 'eams at the pool dec7 le0el, directl, connected to the perimeter col"mns o the '"ildin$, co"ld ha0e led to the col"mns; ail"re and s"'se<"ent collapse o the eastern 9in$ o the '"ildin$. &he sim"lated scenario hihlihts the di erent sta$es o the collapse se<"ence and appears to 'e consistent 9ith 9hat can 'e o'ser0ed in the oota$e o the act"al collapse. &o impro0e the per ormance o the str"ct"re a$ainst pro$ressi0e collapse, t9o modi ications to the ori$inal desi$n o the '"ildin$ 9ere introd"ced. From the anal,ses, it 9as o"nd that disconnectin$ the pool dec7 'eam rom the perimeter col"mns co"ld ha0e 'een e ecti0e in pre0entin$ the local collapse o the pool dec7 sla' rom propa$atin$ to the rest o the '"ildin$. Moreo0er, these anal,ses indicate that enhancin$ the torsional stren$th and sti ness o the core co"ld ha0e pre0ented the collapse o the eastern part o the '"ildin$, $i0en the ass"mptions and initiation scenarios considered.

Ke,9ords= 6"merical !im"lation, Pro$ressi0e Collapse, !tr"ct"ral Fail"re, Applied %lement Method.

PRATICAL APPLICATIONS

#"ildin$ catastrophic collapses can ca"se si$ni icant li0es and economic losses. Poor desi$n and maintenance, in com'ination 9ith ain, 9ill more li7el, increase, in the ne4t ,ears, the n"m'er o '"ildin$s potentiall, 0"lnera'le to the ris7 o collapse, d"e to either seismic, accidental, or de$radation actions. &his research oc"ses on the anal,sis o the Champlain &o9er !o"th condo collapse, 9hich occ"rred in the Cit, o !"r side in 2)21. Di erent h,pothetical collapse scenarios 9ere sim"lated, comparin$ the anal,sis res"lts 9ith the act"al e0idence o the collapse. &he anal,ses ha0e sho9n that the de$radation o the pool dec7 sla', d"e to corrosion, ma, ha0e contri''"ted to the collapse o the '"ildin$. Finall,, t9o di erent minor re0isions o the ori$inal desi$n o the '"ildin$ 9ere anal,(ed to red"ce the ris7 o ail"re and "nderstand ho9 the collapse o similar residential '"ildin$s co"ld 'e pre0ented.

INTRODUCTION

50er the last decades, the n"m'er o p"'lications on themes related to the pro$ressi0e collapse o '"ildin$s has e4ponentiall, increased >Gerasimidis and %llin$9ood 2)23?. &he attention to the disproportionate e ect o a local ail"re dates 'ac7 to 1*.), 9hen the irst re$"lation related to accidental load 9as introd"ced in the 1K code, as a conse<"ence o the partial collapse o the 8onan Point '"ildin$ in 2ondon >@ro"9en0elder 2)21?. Ao9e0er, it 9as a ter the tra$ic terroristic attac7 on the 3orld &rade Center in 2))1 that the pro$ressi0e collapse o str"ct"res capt"red the interest o the academic comm"nit, >2al7o0s7i and !tarosse7 2)22?. !e0eral de initions o Pro$ressi0e Collapse 9ere proposed ', di erent a"thors o0er the last decadesB A!C% .:)5 >A!C% 2))5? de ines pro$ressi0e collapse as C*the spread of an initial local failure from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it”.* &hree common points can 'e identi ied amon$ the di erent proposed de initions= the initial ail"re is local, the ail"re spreads to other str"ct"ral mem'ers, and the inal collapse is disproportionate to the initial ail"re >Kia7oDo"ri et al. 2)21?. *In the last decades, several countries introduced specific regulations to address the risk of progressive collapse.* +n the 1!, the General !er0ice Administration >G!A? code >G!A 2)13? 9as de0eloped or $o0ernment '"ildin$s, 9hile the 1FC 4:)23:)3 code >DoD 2)16? 9as introd"ced or militar, '"ildin$s. +n %"rope, Anne4 A in %"rocode 1 9as introd"ced acco"ntin$ or the irst time or Accidental Actions >C%6 2))6?.

+n contrast 9ith the seismic desi$n o str"ct"res, 9hich is lar$el, addressed in 9orld9ide re$"lations thro"$h a more prescripti0e code compliance approach, pro$ressi0e collapse desi$n o ten re<"ires a per ormance:'ased approach, ', considerin$ a series o C9hat i E scenarios >Fiorillo and Ghosn 2)22?.

Gi0en that the o'Dectí0e o pro$ressi0e collapse desi$n is to ens"re that a str"ct"re can 9ithstand a certain le0el o local dama$e and a0oid collapse propa$ation, it is "nderstanda'le ho9 the prediction o the initial dama$e e ects and its possi'le propa$ation can 'e cr"cial as 9ell as n"mericall, challenin. 50er the past decade, se0eral researchers 9or7in$ on pro$ressi0e collapse desi$n s"$$ested the introd"ction o ro'"stness inde4es. &he, can either 'e 'ased on anal,tical or simpli ied n"merical approaches, s"ch as alternate load:path methods and p"sh:do9n anal,ses >Pra4edes and F"an 2)21?. 3hile 'oth these approaches can 'e e ecti0e in assessin$ the ris7 o pro$ressi0e collapse o relati0el, s,mmetric and homo$eno"s str"ct"ral s,stems, the pro$ressi0e desi$n o comple4 str"ct"ral s,stems ma, re<"ire a more ad0anced methodolo$,, s"ch as the creation o hi$h: idelit, n"merical models >!ade7 et al. 2)22?. 3hile this approach 9as considered prohi'iti0e in the past, 'eca"se o the re<"ired comp"tational e ort, non:linear d,namic anal,ses o hi$h: idelit, n"merical models are no9 easi'le than7s to the latest ad0ancements in hard9are comp"tational capa'ilities and n"merical methodolo$ies >!t,lianidis and 6ethercot 2)21? >2e and #a(ant 2)22?.

Amon$ the n"merical approaches to pro$ressi0e collapse anal,sis, Finite %lement Method, F%M, is 9idel, adopted in se0eral p"'lished st"dies. &he F%M method can 'e e icientl, "sed in pro$ressi0e collapse anal,sis o rame str"ct"res, especiall, in code:'ased proced"res >Kia7oDo"ri et al. 2)2)?. Ao9e0er, 'eca"se the F%M sol0er is 'ased on e<"ili'ri"m e<"ations, the sol"tion cannot a"tomaticall, implement element separations. #eca"se o that, the capa'ilit, to sim"late the entire collapse o the str"ct"re is limited. 6e0ertheless, se0eral strate$ies 9ere de0eloped in recent ,ears to o0ercome F%M limitations in the anal,sis o lar$e displacement pro'lems. For e4ample, the smeared crac7 techni<"e 9as de0eloped to allo9 or crac7 propa$ation in F%M anal,ses >Petran$eli and 5G'olt 1**6?. F%M application to pro$ressi0e collapse anal,sis o entire str"ct"res o ten considers 'i:dimensional rame elements to red"ce the comp"tational '"rden >Alash7er et al. 2)11?. Ao9e0er, researchers also de0eloped a component:le0el, and m"lti:scale models approach ass"min$ the re ined 3D modelin$ o onl, a portion o the str"ct"re >2i and Aao 2)13?, >Mpidi #ita et al. 2)22?. 2astl,, the recent de0elopment o F%M co"plin$ methodolo$, >2" et al. 2))*?, and re ined n"merical proced"re or element remo0al, s"ch as the de$ree:o : reedom >D5F? release >H" et al. 2)1/?, o0ercome the F%M limitations to pro$ressi0e collapse sim"lation.

&he Discrete %lement Method, D%M, 9as also emplo,ed in pro$ressi0e collapse anal,sis >2" et al. 2)1/?. #ased on the compati'ilit, o displacement, the D%M sol0er can acco"nt or element separation and ri$id 'od, collision >Aa7"no and Me$"ro 1**3?B ho9e0er, D%M re<"ires lar$e comp"tational e orts, in partic"lar 9hen dealin$ 9ith a comprehensi0e n"merical model o the entire str"ct"re. &o red"ce anal,sis time and increase the acc"rac, o the res"lts, se0eral F%M:D%M methodolo$ies 9ere also de0eloped o0er the ,ears >2" et al. 2))*?.

Amon$ the n"merical methodolo$ies or str"ct"ral anal,sis, the Applied %lement Method >A%M? is considered one o the most e icient n"merical approaches to collapse anal,sis and sim"lation >Gr"n9ald et al. 2)1/?. &he methodolo$, can a"tomaticall, acco"nt or the ormation o plastic hin$es, de0elopment, and propa$ation o crac7s, 3D load redistri'"tion, as 9ell as ,ieldin$ and ail"re o rein orcin$ 'ars "ntil element separations occ"r >Domaneschi et al. 2)2)?.

&his 9or7 oc"ses on the pro$ressi0e collapse anal,sis o the Champlain &o9ers !o"th condomini"m "sin$ the A%M method. &he 2)21 collapse o the Champlain &o9ers >!"r side, Florida? 9as one o the most catastrophic collapses that e0er occ"rred to rein orced concrete >8C? residential '"ildin$s. #"ilt:in 1*/2 as a part o a three:'"ildin$ comple4, namel, the Champlain &o9ers 6orth, !o"th, and %ast, the Champlain &o9ers !o"th consisted o an 2:shaped, t9el0e:stor, 8C str"ct"re 9ith lat sla's and a 'asement loor co0erin$ the entire ootprint o the '"ildin$ area. 3 hat ma7es this e0ent partic"larl, interestin$ rom the point o 0ie9 o pro$ressi0e collapse anal,sis, is that the e0idence in ers that the collapse 9as ca"sed ', a locali(ed ail"re o a sin$"lar str"ct"ral element. !peci icall,, the ail"re o a sla' d"e to p"nchin$ shear 9o"ld spread to the center o the '"ildin$ irst, and then to the eastern 9in$ a e9 seconds later >2" et al. 2)21?.

&o sim"late collapse scenarios and in0esti$ate the 'eha0ior o the '"ildin$, a hi$h: idelit, A%M n"merical model 9as de0eloped. !e0eral sensiti0it, anal,ses and di erent collapse scenarios 9ere replicated to st"d, the collapse 'eha0ior o the '"ildin$ and e0al"ate the most pro'a'le reason or its collapse. Finall,, the pro$ressi0e collapse per ormance o the str"ct"re 9as enhanced ', introd"cin$ t9o di erent modi ications to the ori$inal desi$n, 9hich co"ld ha0e pre0ented the collapse, "nder the st"died h,potheses.

+t sho"ld 'e noted that the ca"ses o the collapse are c"rrentl, "n7no9n and a comprehensi0e ail"re in0esti$ation ', an a$enc, o the 1! $o0ernment is "nder9a, to pro0ide a de initi0e ans9er as to its ca"ses. &he present 9or7 is 'ased onl, on p"'licl, a0aila'le material, 9hich mostl, re ers to the ori$inal dra9in$s o the str"ct"re 9itho"t considerin$ e0ent"al discrepancies in the inal reali(ation o the '"ildin$. +n addition, the anal,ses presented in this 9or7 are 'ased on ass"med loads, and de$radation conditions 9hich ha0e not 'een 0eri ied.

THE APPLIED ELEMENT METHOD

+n the A%M, the str"ct"re is discreti(ed in a series o si4:de$ree:o : reedom ri$id ei$ht:node elements connected ', (ero:0ol"me sprin$s representin$ 'oth the linear and non:linear 'eha0ior o the constit"ti0e material >Fi$. 1, a?. &he inter ace sprin$s, "ni orml, distri'"ted alon$ the element;s s"r aces, descri'e stresses and de ormation o a certain 0ol"me δ@. A $eometrical relation is determined 'et9een the centroid o the ei$ht:node element and the contact point in 9hich the s"r ace sprin$ is located >Fi$. 1, '?. &he a4ial sti ness, >7_n? and shear sti nesses, >$7_{s,1}$, $7_{s,2}$? o the inter ace sprin$s are determined 'ased on the $i0en elastic mod"li, % and G, and the area >dIt? and len$th >l? o the represented i:0ol"me, as per the ollo9in$ e<"ations=

$$7_n J \%dt\mathrm{K}l\mathrm{B}\ 7_{s,1,2} J Gdt\mathrm{K}l \qquad \%<. 1$$

More details a'o"t the methodolo$, can 'e o"nd in &a$el:Din and Me$"ro >2)))?.

+n the A%M approach to the anal,sis o 8C str"ct"res, the mechanical 'eha0ior o the concrete material is represented ', a series o sprin$s distri'"ted alon$ the inter ace 'et9een the t9o elements >Fi$. 1, c?. &he contri'"tion o steel re'ars em'edded in the material can 'e e4plicitl, acco"nted or ', co"plin$ the mechanical contri'"tion o additional sprin$s representin$ the steel rein orcement. &he steel sprin$s are placed in their act"al position in the cross:section o the considered str"ct"ral element >Fi$. 1, d?. As the sprin$s consider the a4ial sti ness 7_n, and the shear sti nesses $7_{s,1}$ and $7_{s,2}$, the contri'"tion o 'oth lon$it"dinal and trans0ersal rein orcin$ 'ars, or the $i0en constit"ti0e la9s, is a"tomaticall, acco"nted or in the n"merical anal,sis. +n this st"d,, the Mae7a9a and 57am"ra >1*/5? model is considered or representin$ the a4ial 'eha0ior o concrete >Fi$. 1, e?, 9hile a linear relationship "p to ail"re is ass"med or the 'eha0ior o concrete s"'Dect to com'ined shear and compressi0e loads >Fi$. 1, ?. Finall,, the Mene$otto and Pinto >1*.3? model is adopted or representin$ the nonlinear 'eha0ior o steel rein orcement >Fi$. 1, $?.

Fi$. 1. A%M discreti(ation approach o 8C assem'lies and the correspondin$ constit"ti0e la9s or concrete and steel.

&he commercial so t9are %4treme 2oadin$ or !tr"ct"res >%2!? de0eloped ', Applied !cience +nternational >A!+? 9as emplo,ed in the present st"d, >A!+, 2)21?.

THE AEM NUMERICAL MODEL OF THE CHAMPLAIN TOWERS CONDO

Structure description and material properties

&he Champlain &o9ers !o"th str"ct"re consists o 8C lat sla's s"pported ', 8C col"mns. &he thic7ness o the sla' is 23 cm >*E? on the 'asement loor, 24 cm >* LE? at the 2o'', le0el, and 2)cm >/E? or t,pical loors. Di erent concrete compressi0e stren$ths 9ere considered in the desi$n o the '"ildin$= col"mns and shear 9alls 9ere desi$ned 9ith stren$th 0ar,in$ rom 41 MPa >6))) psi? to 2/ MPa >4))) psi?, 9hile the sla's 9ere desi$ned 9ith compressi0e stren$th 0ar,in$ rom 2/ MPa >4))) psi? to 21 MPa >3))) psi?, >Fi$. 2, a?. &he lon$it"dinal rein orcement o col"mns is 0ar,in$ rom si(e M36 mm >N11? at the lo9er loors to M25 mm >N/? at the "pper loors. &he rein orcement o the t9o shear 9alls incl"des t9o col"mns at each ed$e and a rein orcement M13 mm >N4? mesh, spaced at 3) cm >12E?. M13 mm >N4? stirr"ps 9ere "sed or M36 mm >N11? lon$it"dinal rein orcement 9hile M1) mm >N3? stirr"ps 9ere "sed or the rest o the 'ar si(es, >Fi$. 2, '?.

Fi$. 2. Color map o concrete stren$th in col"mns, shear 9alls, and sla's >a? 0MPa *(ksi)*P, and diameter o rein orcement 'ars implemented in the n"merical model >'? 0mmP

&a'le 1 sho9s the concrete properties considered or the A%M n"merical model.

&a'le 1. Concrete material properties introd"ced in the A%M n"merical model 0!tresses in MPa >*ksi)*, %lastic Mod"l"s in GPa >*Mpsi)*P

&he 'ottom rein orcement o the lat sla' consists o a "ni orm re'ar mesh o M13 mm >N4? spaced at 3) cm >12E? in the 'asement and 2o'', loors, and 33 cm >13E? at the 2nd and t,pical loors. &he p"nchin$ shear rein orcement at the top side o the sla' consists o M16 mm >N5? re'ars 9ith 0aria'le spacin$. &he area co0ered ', the p"nchin$ shear rein orcement also 0aries 'ased on the col"mn;s section and location. 8e'ars ha0in$ a diameter o M13 mm >N4? and di erent spacin$s 9ere pro0ided, in one direction onl,, at the top side o the sla's, in the transition (ones 'et9een the areas co0ered 9ith p"nchin$ shear rein orcement >Fi$. 3?.

Fi$. 3. A%M n"merical model 0ie9 o the p"nchin$ shear rein orcement in the lo'', sla', 'asement, 2nd loor, and t,pical loor.

8C $irders can 'e o"nd in the 2o'', and 2nd loor onl,. 5n the 2o'', loor, 3)cm >12E? 9idth $irders 9ith 0ario"s depths are connectin$ the 2o'', 8C sla's at di erent ele0ations >also re erenced as Csla':dropsE in the ori$inal dra9in$s o the str"ct"re?. 5n the 2nd loor, *141). cm

>36E4 42E? trans er $irders are s"pportin$ 3),5461cm >12E424E? col"mns ele0atin$ rom the 2nd loor to the roo .

As speci ied in the as:'"ilt dra9in$s notes >3illiam M. Friedman Q Associates Architects 1*.*?, rein orcin$ 'ars meet A!&M A:615 Grade 6) criteria, 9ith ,ield stren$th e<"al to 414 MPa >*60 ksi*?, >&a'le 2?.

&a'le 2. !teel material properties introd"ced in the A%M n"merical model 0!tresses in MPa >*ksi)*, %lastic Mod"l"s in GPa >*Mpsi)*P

&he inal de0eloped model, emplo,in$ 5 matri4 sprin$s per element;s ace, res"lted in ..5 million matri4 sprin$s representin$ the di erent concrete materials and additional)./5 million e<"i0alent sprin$s representin$ the di erent rein orcement or more than *)),))) de$rees o reedom.

&he non:linear d,namic anal,ses 9ere per ormed considerin$ a time step e<"al to).))1 s, "sin$ a 3.5 GA(12 cores processor and re<"estin$ appro4imatel, 3) G' o memor,. 3ith the $i0en hard9are, the A%M sol0er prod"ced the anal,sis o"tp"t o 1 sec in appro4imatel, 3 ho"rs o calc"lations, res"ltin$ in o0erall 4/ ho"rs needed to complete one entire collapse sim"lation o the d"ration o appro4imatel, 16 sec.

Loads

&he dead load o the str"ct"ral elements e4plicitl, introd"ced in the n"merical model is a"tomaticall, acco"nted or in the anal,sis 'ased on the 0ol"me and densit, o the concrete. +n addition, the 9ei$ht o non:'earin$ 9alls, inishes, "rnit"re, and an, other elements not directl, introd"ced in the n"merical model 9as ass"med as distri'"ted on the loor area. As this 9or7 aims to compare the n"merical res"lts 9ith the act"al e0idence o the Champlain &o9er !o"th collapse, no code:'ased load com'inations are considered in the anal,sis. +n act, 9ith respect to the DoD and G!A pro0isions, in 9hich a actor o 1K2 is applied to the prescri'ed 2i0e 2oad, 22, onl, a raction o 1K422 is ass"med to 'e in place at the moment o the collapse. &he ass"mption is consistent 9ith

A!C% .:22 Commentar, &a'le C4.3:2, 9hich s"$$ests a mean s"stained 2i0e 2oad o).37 6Km^2 *(≈6 lb/ft^2*?, >A!C% 2)21?. +n addition, 'eca"se o "ncertainties on apartment; inishes, 9alls and ceilin$s composition and materials, and o0erall act"al loads at the moment o the collapse, sensiti0it, anal,ses 9ere carried o"t 9ith di erent loadin$ ass"mptions, considerin$ a c"m"lati0e distri'"ted load >D2R22? 0ar,in$ rom 1.5 76Km^2 >*≈30 lb/ft^2*? to 3.) 76Km^2 >*≈60 lb/ft^2*?. +n this 9or7, onl, the anal,ses 9ith the load ass"mptions reported in &a'le 3 are considered or the sa7e o 're0it,.

&a'le 3. 2oads 076Km^2 >*lb/ft^2)*P

For the &,pical Floor, the ollo9in$ loads 9ere ass"med 'ased on the t,pical 9ei$hts o the '"ildin$ materials >#re,er et al. 2)2)?= dead load in addition to sla' sel :9ei$ht, 1 76Km^2 >*20lb/ft^2*?, acco"ntin$ or the loor inishes, ceilin$s, aSade elements, 9indo9s, doors, railin$s, M%P s,stems, and an, additional load not e4plicitl, introd"ced in the modelB dead load o 9alls Q partitions,).5 76Km^2 >*10lb/ft^2*?B li0e load,).5 76Km^2 >*10lb/ft^2*?B the total considered distri'"ted load res"lts 2 76Km^2 >*40lb/ft^2*?.

+n addition to the distri'"ted load, an ornamental plant load, estimated on a soil densit, e<"al to 16 76Km^2 >*≈100 lb/ft^3*?, 9as introd"ced in the n"merical model at the pool dec7 le0el 'ased on the act"al plant arran$ements at the time o the collapse.

NON-LINEAR DYNAMIC ANALYSES AND COLLAPSE SCENARIOS

&9o o the most credited h,potheses raised ', media in the a termath o the collapse o the Champlain &o9ers !o"th attri'"te the ca"se to either di erential settlement in the o"ndations or locali(ed str"ct"ral ail"re. +n the irst sta$e o this 9or7, se0eral col"mn remo0al scenarios 9ere carried o"t to e0al"ate the sensiti0it, o the str"ct"re to col"mn ail"re and its conse<"ent load redistri'"tion capacit,.

Column removal scenarios

Col"mn remo0al scenarios 9ere implemented at the locations 9here the initial ail"re 9as o'ser0ed, considerin$ 'oth perimeter and inner col"mn remo0al scenarios. &o sim"late a h,pothetical o"ndation settlement, col"mns are remo0ed at the o"ndation pile le0el, 'elo9 the 'asement sla'. &h"s, the 'asement sla' contri'"tes to the load redistri'"tion till p"nchin$ shear ail"re occ"rs. &he col"mn;s remo0al is per ormed "sin$ non:linear static anal,sis, so the o0erload determined ', the col"mn;s loss is redistri'"ted incrementall, to the s"rro"ndin$ str"ct"ral elements. &he t9o considered scenarios, loss o center col"mns and loss o perimeter col"mns, 9ere de ined to identi , the most pro'a'le area 9here the initial ail"re occ"rred. %ach o the t9o scenarios 9as repeated considerin$ the loss o one col"mn irst, and an adDacent one a ter, 7eepin$ remo0in$ col"mns till collapse is reached.

&he col"mn remo0al anal,ses re0ealed that the '"ildin$ 9as more sensiti0e to the remo0al o perimeter col"mns >Fi$. 4, scenarios C and D? rather than inner col"mns >Fi$. 4, scenarios A and #?. +n act, "nder the loadin$ ass"mption and considerin$ the ori$inal properties o steel and concrete, 9itho"t acco"ntin$ or material de$radation, the '"ildin$ 9as a'le to redistri'"te the loads and a0oid pro$ressi0e collapse, e0en 9hen three inner col"mns 9ere remo0ed >Fi$. 4, !cenario #?. 6e0ertheless, the remo0al o t9o perimeter col"mns 9as eno"$h to initiate the pro$ressi0e collapse o the '"ildin$ >Fi$. 4, !cenario D?.

Fi$. 4. +nner >top? and perimeter >'ottom? col"mn remo0al scenario, @ertical de lection.

A load sensiti0it, anal,sis 9as also carried o"t sho9in$ that the scenario o perimeter col"mn remo0al remains the most critical one re$ardless o the entit, o load.

Localized degradation scenario

!e0eral media disc"ssed e0idence o e4tensi0e de$radation o the pool dec7 sla' in the immediate a termath o the collapse. +ndeed, the area 9as partiall, co0ered ', ornamental plants, 9hich, on top o the additional 9eiht, miht also ha0e ca"sed corrosion o the sla' steel rein orcement d"e to 9aterin$ and lac7 o proper impermea'ili(ation. !tatic anal,ses 9ere per ormed considerin$ onl, the 0ertical dead load, as per load ass"mptions, 9itho"t acco"ntin$ or an, de$radation. &hese anal,ses sho9ed that the area o the pool dec7 9as s"'stantiall, 9ea7er and s"'Dected to hi$her de lections and stresses than the area 9ithin the t9el0e:stor, '"ildin$ ootprint >Fi$. 5, a?. For e4ample, the de lection in the pool dec7 area reaches 2cm, 9hile it res"lted in onl, ractions o a centimeter in the area pertainin$ to the t9el0e:stor, '"ildin$ itsel . &he lar$er spans, to$ether 9ith the limited rein orcement, led to stresses in the p"nchin$ shear rein orcement s"'stantiall, hi$her than in the rest o the str"ct"re. &he mean 0al"e o normal stresses in the p"nchin$ shear rein orcin$ 'ars on the $ro"nd loor o the t9el0e:stor, '"ildin$ 9as o"nd to 'e 'elo9 1))MPa >T157si?. +n the pool dec7 area, the normal stresses in the p"nchin$ shear rein orcin$ 'ars reached 2))MPa >T3)7si?, 9hich corresponds to hal o the ,ield stress o the steel, 414MPa >6)7si?, accordin$ to the ori$inal desi$n speci ication >3illiam M. Friedman Q Associates Architects 1*.*?. +n partic"lar, the area 9here the initial collapse occ"rred, sho9ed the hi$hest stresses, speci icall, at the top side re'ars o the pool dec7 sla' >Fi$. 5, '?.

Fi$. 5. !tatic anal,sis, @ertical displacement at 'asement le0el 0cm >*in*?P >a?, and normal stresses in top p"nchin$ shear rein orcement 0MPa >*Ksi*?P >'?

&o in0esti$ate the h,pothesis o the pool dec7 sla' de$radation, "rther anal,ses 9ere per ormed considerin$ locali(ed steel de$radation in the pool dec7 area >Fi$. 6?.

Fi$. 6. #"ildin$ plan at 'asement le0el 9ith the indication o the t9el0e:stor, '"ildin$;s ootprint and the de$raded area o the pool dec7 le0el

De$radation anal,ses 9ere carried o"t ', introd"cin$ a pro$ressi0e area red"ction o the sla' and 'eams rein orcement, "p to *)U, "ntil collapse is reached. &his de$radation anal,sis approach is 9idel, adopted in the literat"re. For instance, it 9as "sed to anal,(e the collapse o the Polce0era @iad"ct in Genoa, +tal, >Domaneschi et al. 2)2)?.

Fi$. . sho9s a comparison 'et9een the crac7 distri'"tion res"ltin$ rom the t9o considered scenarios, o"ndation settlement in the center o the '"ildin$ >Fi$. ., a? and de$radation o the pool dec7 sla' >Fi$. ., '?.

Fi$. .. 2o'', le0el, comparison 'et9een crac7s distri'"tion in case o o"ndation settlement scenario >le t? and pool dec7 de$radation scenario >ri$ht?, Principal strains in Dir.1 0:P

Crac7s are sho9n 'ased on the plot o principal normal strains, 0ar,in$ rom εJ).) to εJ).1. Considerin$ a mesh dimension e<"al to appro4imatel, 3)cm >T1 t?, it corresponds to a ma4im"m crac7 openin$ o a'o"t 3cm >T1in?. +t can 'e noticed ho9 a di "se o"ndation settlement, 9hich sho"ld ha0e in0ol0ed at least o"r col"mns to res"lt in the disproportionate collapse o the '"ildin$ >see CCol"mns remo0al scenariosE?, 9o"ld ha0e ca"sed 9idespread crac7in$ and concrete spallin$ at the 'asement le0el that ', ar e4ceeds 9hat is descri'ed in the reports a'o"t the str"ct"re >Fi$. ., a?. %0idence o linear crac7in$ at the Pool dec7 sla', o"tside the act"al ootprint o the '"ildin$, 9as instead reported ', some media and o"nd in the de$radation anal,sis scenario also >Fi$. ., '?.

+n addition, it 9as noticed that, 9hen appl,in$ the de$radation to 'oth the spans pertainin$ to the t9el0e:stor, '"ildin$ and the pool dec7 sla', the pool dec7 sla' area 9o"ld ha0e sho9n m"ch more di "se e0idence o crac7s compared to the t9el0e:stor, '"ildin$ co"nterpart, 'eca"se o the inherent lo9er resid"al capacit,, deri0in$ rom ornamental plant s"perimposed load and lar$er spans.

Another aspect 9orth noticin$ is that the pool dec7 str"ct"re, desi$ned to carr, onl, one loor rather than t9el0e stories, 9hile also s"'Dect to additional s"perimposed loads and deterioration, 9as ri$idl, connected to the main str"ct"re thro"$h three 'eams 9ith a depth o 46cm >*18”*?.

&hese 'eams 9ere $enerall, "sed at the pool dec7 sla' le0el to co0er or di erent ele0ations and steps, and in act, called Csla' dropsE.

&he three pre0io"sl, mentioned Csla' dropsE 9ere ori$inall, desi$ned to 'e 5*cm >*23”*?, and then red"ced to 46cm >*18”*? in a second desi$n re0ision >3illiam M. Friedman Q Associates Architects 1*.*?. &he de$radation anal,sis o the pool dec7 sla' sho9s ho9 the depth o the three

$irders, res"ltin$ rom the sla' drops, co"ld ha0e pla,ed a si$ni icant role in propa$atin$ the collapse o the sla' to the rest o the '"ildin$. #eca"se the '"ildin$ 9as partic"larl, sensiti0e to the loss o perimeter col"mns, 9hen the sla' and connectin$ 'eams ail, a concentrated 'endin$ moment is trans erred to the three perimeter col"mns, leadin$ to col"mn o0erload and conse<"ent collapse o the '"ildin$ >Fi$. /?.

Fi$. /. % ect o deep 'eams in ca"sin$ the insta'ilit, o the perimeter col"mns at 2.)s, Principal strains in Dir.1, !cale color red e<"al to).1 !train 0:P, and de ormed shape scaled ', a actor o 2 >le t?

Arch and catenary actions: from the failure of the pool deck slab to the disproportionate collapse of the building

&his section descri'es the identi ied collapse mechanism, startin$ rom the dec7 ail"re, ollo9ed ', the ormation o an arch action and s"'se<"ent catenar, action, "ntil reachin$ the ail"re o the perimeter col"mns.

Fi$. * sho9s a time:lapse o the ail"re at di erent seconds, descri'in$ 'oth the 0ariation o compressi0e stresses in the concrete, normal stresses in the rein orcin$ 'ars, and the 0ariation o internal orces in col"mns and 'eams, as the ail"re pro$resses. &he di erent instants are identi ied in the timeline at the 'ottom o the Fi$"re. &he compressi0e stresses in the concrete are sho9n in the top ro9B Also, the stresses in the rein orcin$ 'ars are sho9n in the middle ro9, to$ether 9ith the related chromatic scaleB the compressi0e stresses in the Finall,, the internal orces, 'endin$ moment, M, >positi0e in red and ne$ati0e in 'l"e?, and normal orce, 6, >in ma$enta? are sho9n on the 'ottom ro9.

Fi$. *. Col"mn 11.1:2, Compressi0e stresses in the concrete 0MPa *(Ksi)*P >top?, normal stresses in 'eams; and col"mns; rein orcement 0MPa *(Ksi)*P, normal orces 076 *(kips)*P in the col"mn and 'endin$ moments in the 'eams 076Vm *(kips*inch)*P >'ottom?, at di erent sta$es o the collapse.

3hen de$radation is introd"ced, steel re'ars start ,ieldin$. &he sla' starts de lectin$ do9n9ards and the concrete in the perimeter col"mns reaches its ma4im"m compressi0e stren$th at the connection 9ith the pool dec7 'eams >Fi$. *, 1.)s?. A ter the concrete ails, as a conse<"ence o the ,ieldin$ o the lon$it"dinal rein orcement in the pool dec7 'eams, the 'endin$ moment in the col"mn increases till reachin$ the "ltimate capacit, o the section or the $i0en com'ination o a4ial orces and moment >Fi$. *, 1.3s?. At this point the col"mn loses its load:'earin$ capacit,, acti0atin$ an initial arch action, as can 'e $athered rom the increase o compressi0e stresses at the top o the perimeter 'eams >Fi$. *, 1.5s?. Conse<"entl,, the col"mn:'eam connection ails, $eneratin$ a catenar, action in the perimeter 'eams that res"lts in 'oth top and 'ottom lon$it"dinal rein orcement s"'Dected to tensile stresses >Fi$. *, 2.)s?. At this point, the ori$inal de$radation introd"ced in the sla' has pro$ressed thro"$h sla' ail"re and s"'se<"ent col"mn ail"re, 9ith the onl, catenar, action opposin$ the propa$ation o the collapse. 1n ort"natel,, the amo"nt o rein orcement in the 'eams is not eno"$h to 9ithstand the catenar, orces, "ltimatel, leadin$ to the pro$ressi0e collapse o the '"ildin$ >Fi$. 1)?.

Fi$. 1). Distri'"tion o Principal !trains 0:P a ter col"mn; ail"re >le t?, and p"nchin$ shear ail"re at pool dec7 sla' >ri$ht?

Side-by-side comparison of the collapse

Fi$. 11 sho9s a side:',:side comparison 'et9een the sim"lation and the oota$e o the collapse >!later 2)21?. &he comparison sho9s a $ood a$reement 'et9een the sim"lations and the act"al collapse, 'oth d"rin$ the initial ail"re o the central portion o the '"ildin$ >'et9een A4es G and M, Fi$. 6?, and the initial torsion o the remainin$ eastern portion o the '"ildin$, a e9 instants later. Ao9e0er, a le4"ral ail"re at mid:hei$ht o the eastern 9in$ o the str"ct"re can 'e o'ser0ed onl, in the n"merical anal,sis, occ"rrin$ 9hen the remainin$ portion o the str"ct"re starts hittin$ the $ro"nd > rame &. in Fi$.11?.

Fi$. 11. !ide:',:side comparison 'et9een the oota$e o the collapse and the n"merical anal,sis in nine di erent timestampsB +ma$e co"rtes, o !later >2)21?.

&his ail"re, 9hich ta7es place appro4imati0el, at the middle hei$ht o the str"ct"re, res"lts in more than hal o the eastern core o the '"ildin$ leanin$ to9ard the east in the inal de'ris distri'"tion o'tained rom the n"merical anal,sis. Ao9e0er, this mechanism is not o'ser0ed in the act"al 0ideo o the ail"re, 9here the eastern 9in$ collapses in on itsel , leanin$ to9ard the 9est. &he di erence in the o'ser0ed collapse 'eha0ior co"ld 'e e4plained ', a possi'le di0er$ence o the mechanical properties o the materials, d"e to either de$radation or constr"ction de ects, 9hich are not considered in the model.

Fi$. 12 sho9s a comparison 'et9een the reconstr"ction o the act"al de'ris distri'"tion res"ltin$ a ter the collapse and the de'ris res"ltin$ rom the anal,sis.

Fi$. 12. Comparison 'et9een act"al de'ris distri'"tion >a? and anal,sis res"lts >'?B +ma$e >a? reconstr"cted ', the A"thors 'ased on a0aila'le media pict"res.

+n 'oth cases, the collapse o the '"ildin$ did not spread o0er the 9est core o the str"ct"re. &he initial torsion o the eastern 9in$ is also capt"red ', the n"merical anal,sis, as it can 'e $athered rom the orientation o the sla's, pointin$ to9ards the so"th side. Ao9e0er, 'eca"se o the le4"ral ail"re mechanism descri'ed earl,, 9hich 9as o'ser0ed in the n"merical sim"lation onl,, the inal position o the east shear 9all core di ers, 9ith the hal :eastern core leanin$ east rather than 9est.

PROGRESSIVE COLLAPSE ANALYSIS UNDER ALTERNATIVE DESIGN SCENARIOS

+n0esti$atin$ ho9 the ail"re propa$ation co"ld ha0e 'een pre0ented, co"ld help a0oid similar catastrophic e0ents in the "t"re. &o a0oid the disproportionate collapse o the '"ildin$, t9o alternati0e desi$ns 9ere de ined.

&he irst alternati0e desi$n scenario considers that the pool dec7 sla' is not connected to the main str"ct"re thro"$h deep 'eams. &h"s, the deep 'eams connectin$ the sla' to the perimeter col"mns 9ere remo0ed >Fi$. 13, a, '?. As it 9as pre0io"sl, noted in this 9or7, the three deep 'eams 9ere pro0ided in the desi$n as Csla' dropE, to co0er the di erent ele0ations at the pool dec7 area.

&he sla' rein orcement in this area 9as the same as the s"rro"ndin$ spans, ha0in$ similar span len$ths and loads '"t 9ith no deep 'eams. &here ore, the scenario onl, pertains to the remo0al o the Csla' dropsE and related di erences in ele0ation, 9itho"t modi ications to the ori$inal desi$n o the sla's.

+n this con i$"ration, e0en 9hen ass"min$ hi$h de$radation o the pool dec7 sla', perimeter 'eams, and col"mns, the ail"re o the sla' did not a ect the rest o the str"ct"re >Fi$. 13, c?. #eca"se the sla' has a s"'stantiall, smaller depth compared to one o the deep 'eams, the 'endin$ moment ind"ced to the col"mn Doint is considera'l, smaller. &here ore, 9hen the sla' ails, p"nchin$ shear ail"re occ"rs and the sla' detaches rom the perimeter col"mns 9itho"t compromisin$ their load: 'earin$ capacit, >Fi$. 13, d?.

Fi$. 13. 5ri$inal desi$n >a?, and alternati0e scenario >'?, ass"min$ the a'sence o 'eams connectin$ perpendic"larl, the pool dec7 to the perimeter col"mn o the str"ct"re, Anal,sis res"lts, @ertical displacement >c? 0cm >*in*?P, and Principal strains at sla' ail"re >d? 0:P

+n terms o pro$ressi0e collapse desi$n, it is clear ho9 the str"ct"ral separation 'et9een the main t9el0e:stor, '"ildin$ and the secondar, str"ct"re >i.e., one:stor, 'asement?, co"ld 'e an e ecti0e strate$, in a0oidin$ collapse propa$ation, especiall, 9hen the secondar, str"ct"re is nat"rall, s"'Dect to deterioration >e.$., terraces, pool dec7s, etc.?.

&he second alternati0e desi$n scenario considers the introd"ction o additional shear 9alls in the %ast core o the '"ildin$ >Fi$. 14, a, c?. &he o'Decti0e is to red"ce the torsional 'eha0ior o'ser0ed d"rin$ the collapse o the eastern 9in$ o the '"ildin$ and a0oid its ail"re >Fi$. 14, e?.

&he reason 9h,, a ter the collapse o the central portion o the '"ildin$, the collapse propa$ated to the eastern 9in$ onl,, is related to the di erent torsional sti ness res"ltin$ rom the str"ct"ral la,o"t. 3hile the 3est core o the '"ildin$ consisted o 8C shear 9alls oriented 'oth in the 6orth:!o"th and %ast:3est directions, the %ast 8C core o the str"ct"re 9as composed o onl, one shear 9all oriented in the 6orth:!o"th direction. &here ore, the torsional capacit, o the 9estern core 9as si$ni icantl, lar$er than the one o the eastern core. 3hen the central 'loc7 o the '"ildin$ starts ailin$, it 9as o'ser0ed that sla's 9ere detachin$ rom the 9estern and eastern 9in$s at the inter ace o the shear 9all. A ter9ard, the eastern 9in$ ails, d"e to the lac7 o torsional capacit,. +n li$ht o that, t9o additional shear 9alls 9ere introd"ced in the %ast: 3est direction >Fi$. 14, c?. 8es"lts sho9 that the chan$e in the desi$n is e ecti0e in a0oidin$ the collapse o the eastern 9in$ >Fi$. 14, d, ?. &he di erence in terms o rotation o'ser0ed 'oth in the ori$inal model and in the ne9 desi$n con i$"ration can 'e e0al"ated rom, Fi$. 14, e, .

Fi$. 14. 5ri$inal desi$n >le t?, and alternati0e scenario >ri$ht?, ass"min$ the presence o t9o additional shear 9alls

+n terms o pro$ressi0e collapse desi$n, these res"lts hihlihted that pro0idin$ 8C cores 9ith eno"$h torsional capacit, can 'e e ecti0e in pre0entin$ collapse propa$ation 'et9een di erent parts o the str"ct"re.

CONCLUSIONS

+n this 9or7, a series o pro$ressi0e collapse anal,ses 9ere per ormed to anal,(e the collapse o the Champlain &o9ers !o"th in 2)21 >!"r side, Florida?. An A%M hi$h: idelit, n"merical model 9as de0eloped and emplo,ed to in0esti$ate the possi'le ca"ses o the collapse. Di erent col"mn remo0al scenarios 9ere modeled to sim"late o"ndation settlement, 9hile str"ct"ral de$radation 9as modeled pro$ressi0el, red"cin$ the rein orcement cross:section area. Col"mn remo0al anal,ses re0ealed that the '"ildin$ 9as partic"larl, sensiti0e to the loss o perimeter col"mns, 9hose ail"re co"ld easil, propa$ate to the central 'loc7, d"e to the lac7 o load redistri'"tion capacit, at the perimeter o the str"ct"re. +n addition, the de$radation anal,sis at the pool dec7 le0el sho9ed that the initial ail"re o the pool dec7 sla' co"ld ha0e ca"sed rele0ant dama$e to the connection 'et9een the perimeter col"mns and the pool dec7 'eams, leadin$ to the ail"re o the perimeter col"mns. +ndeed, the $lo'al static anal,sis re0ealed that the one:stor, str"ct"re o the pool area 9as s"'Dected to hi$her de lections and stresses than those o"nd in the main '"ildin$. &he side:',:side comparison 'et9een the sim"lated collapse thro"$h nonlinear d,namic anal,sis and the act"al oota$e o the e0ent sho9ed a reasona'le match.

&9o 0ariations to the ori$inal desi$n 9ere introd"ced aimin$ at a0oidin$ the collapse propa$ation rom the pool dec7 to the main str"ct"re and the collapse o the eastern 9in$ o the '"ildin$. +t 9as o"nd that the remo0al o the deep 'eams connected to the perimeter col"mns at the pool dec7 le0el 9as e ecti0e in pre0entin$ the initial ail"re o the pool dec7 sla' rom propa$atin$ to the rest o the '"ildin$. +n addition, increasin$ the torsional capacit, o the eastern 9in$ ', introd"cin$ t9o shear 9alls oriented in the %ast:3est direction, 9as pro0en to 'e e ecti0e in pre0entin$ its collapse. &he o0erall separation 'et9een str"ct"res o di erent nat"res, s"ch as one: stor, 'asements and t9el0e:stor, '"ildin$s, and 8C cores consistin$ o shear 9alls oriented alon$ the t9o principal directions, are the main lessons learned rom the pro$ressi0e collapse anal,sis o the tra$ic Champlain &o9ers !o"th collapse.

DATA AVAILABILITY STATEMENT

!ome or all data, models, or codes that s"pport the indin$s o this st"d, are a0aila'le rom the correspondin$ a"thor "pon reasona'le re<"est.

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!later or pro0idin$ the permission to "se some shots rom the 0ideo sho9in$ the collapse o the Champlain &o9er !o"th Condo >!later 2)21?.

NOTATIONS

The following symbols are used in this paper:

% J elastic mod"l"s >GPa?B

c J compressi0e stren$th o concrete >MPa?B

t J tensile stren$th o concrete >MPa?B

G J shear mod"l"s >GPa?B

G_i J element;s centroidB

$7_{c,n}$ J normal sti ness o concrete sprin$s

$7_{c,s}$ J shear sti ness o concrete sprin$s

$7_{r,n}$ J normal sti ness o rein orcement sprin$s

$7_{r,s}$ J shear sti ness o rein orcement sprin$s

8&F J rein orcin$ 'arsB

"i J element;s de$ree o reedomB

ε" J "ltimate strain o steelB

μ J riction coe icientB

$\sigma_,$ J ,ield stress o steel >MPa?B

$\sigma_"$ J "ltimate stress o steel >MPa?B

τs J shear stren$th o concrete >MPa?B

SUPPLEMENTAL DATA STATEMENT

Fi$s. !1W!14 are a0aila'le online in the A!C% 2i'rar, >asceli'rar,.or$?.

8%F%8%6C%!

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C%6 >2))6?. XActions on str"ct"res:Part 1:.= General actions:Accidental actions. %6 1**4:1:1, %"rocode 4.X, %. C. . !tandardisation, ed.#r"ssels, #el$i"m.

DoD >2)16?. X1ni ied acilities criteria= Desi$n o '"ildin$s to resist pro$ressi0e collapse. 1FC 4:)23:)3, chan$e 3, 6o0em'er 2)16.X D. o. De ense, ed. 3ashin$ton, DC.

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&a'le 1. Concrete material properties introd"ced in the A%M n"merical model 0!tresses in MPa >*ksi)*, %lastic Mod"l"s in GPa >*Mpsi)*P

Concrete	f_c	f_t>a?	τ_s>'?	μ 0:P	%>c?	G>d?
6)))psi	41 >*6)*	4 >*0.6)*	13 >*1.9)*	)./	32 >*4.7)*	13 >*1.9)*
5)))psi	34 >*5)*	3 >*0.5)*	12 >*1.8)*	)./	2* >*4.3)*	12 >*1.8)*
4)))psi	2/ >*4)*	3 >*0.4)*	11 >*1.6)*	)./	26 >*3.8)*	11 >*1.6)*
3)))psi	21 >*3)*	2 >*0.3)*	1) >*1.5)*	)./	23 >*3.3)*	* >*1.4)*

6ote= a f_tJf_cK1)B ' τ_sJ3./ f_c).33B c %c J 5)))V> c7]>1K2??, 0MpaPB d GJ %K>2>1Rv??, vJ).2

&a'le 2. !teel material properties introd"ced in the A%M n"merical model 0!tresses in MPa >*ksi)*, %lastic Mod"l"s in GPa >*Mpsi)*P

!teel	σ,	σ"	ε"	%	G
Grade6)	414 >*60)*	5.* >*84)*	1	2)) >*29)*	/) >*12)*

&a'le 3. 2oads 07 6Km^2 >*lb/ft^2)*P

Floor	Dead load in addition to sla' sel :9ei$ht	Dead 2oad o 9alls Q partitions	2i0e 2oad	&otal per loor
&,pical	T1.) >*20)*	T).5 >*10)*	T).5 >*10)* (a)	T2.) >*40)*
2o'',	T2.) >*40)*	T).5 >*10)*	T1.) >*20)*	T3.) >*60)*
#asement	:	:	T1.) >*20)* (b)	T1.) >*20)*

6ote= a 1K4 o 2.)76Km^2 *(≈40lb/ft^2*? desi$n load or residential '"ildin$sB ' 1K2.5 o 2.576Km^2 >≈*50lb/ft^2*? desi$n load or araes.

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