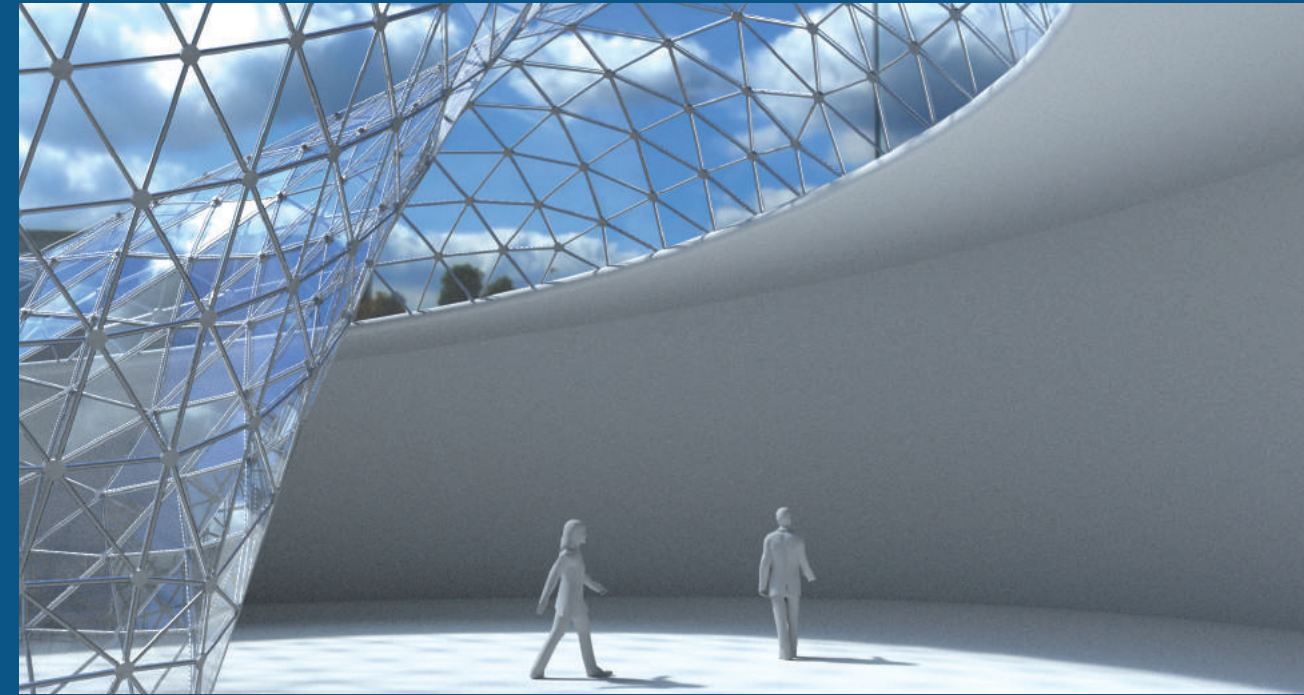




University of Pisa | DESTeC
Department of Energy, Systems, Territory and Construction Engineering
XXXI Cycle



Francesco Laccone



Ph.D. Dissertation

Reinforced and post-tensioned structural glass shells

Concept, morphogenesis and analysis

Reinforced and post-tensioned structural glass shells

Pisa, Italy. March 2019

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A mio nonno
Ai miei genitori e a Domenico
A Francesca

Preface

The relationship between architecture and structure is a key point in the conceptual phase of a building or one of its components. Glass structures can be considered optimal from the material usage viewpoint because they simultaneously offer transparency, an idea always pursued by architects, and good structural performances.

Transparent and free-form glass shells are fascinating objects from both the aesthetic and structural engineering point of view, but are practically difficult to realize, apart from limited favourable cases, and have a low safety level. This work explores a new structural concept for triangulated glass shells, in which the glass panels are both reinforced and post-tensioned. Hence, the net formed by the reinforcements constitutes a redundancy barrier to avoid global collapse in case of glass cracking.

In order to ensure an adequate safety level, glass should be prevented from carrying tensile stresses. To this aim, a novel algorithm is developed for the automatic design of the piecewise geometry of the shell and the derivation of the optimal cables distribution with respective preloads.

Global nonlinear analyses have been performed to prove the feasibility of the concept and to highlight the advantages that these structures offer with respect to the grid shells competitors. At the local level, the main components of these systems are investigated: the node is tested experimentally and its behaviour is successively described numerically, and the triangular laminated panels are explored with parametric nonlinear models.

The thesis is written as a monograph. Some papers prepared during the study are included as part of the work.

Pisa (Italy), March 2019

Francesco Laccone

Acknowledgements

This doctorate has been for me a growth path with human and scientific enrichment. I wish to acknowledge all people who, with their inestimable contribution, allowed me to achieve this important goal.

This project would not have been realized if not for Prof. Ing. Maurizio Froli, who was promoter and supervisor, and provided for scientific and technical background. This doctorate is rooted in his research on hybrid glass structures. I would like to thank him for this opportunity, for supporting me along the way with inspiring comments and advices, and for funding the specimen and tests.

I would like to acknowledge my co-supervisor Dr. Paolo Cignoni (ISTI-CNR) because his guidance and support led to the development of the algorithmic part of this work. The experience with him within the Visual Computing Lab of ISTI-CNR has been fundamental for my professional growth. This contribution brought significant novelty to structural engineering. Additionally, I owe this developments to Dr. Nico Pietroni (UTS Sydney) and to Dr. Luigi Malomo (ISTI-CNR), who I gratefully thank.

I thank friends and colleagues from the University of Pisa, the Visual Computing Lab (ISTI-CNR) and the TU Delft for sharing ideas and stimulating multi-disciplinary debates around many aspects of this work.

I would like to thank Dr. ir. Christian Louter for hosting me at TU Delft within Glass & Transparency Research Group, for the important and appreciated suggestions on the state of the art and on how to structure my work, and finally for the supervision of the research included in chapter 11.

The experimental work, whose results are included in this thesis, was made possible thanks to the assistance of Dr. Ing. Giuseppe Chellini, and the laboratory staff Michele Di Ruscio, Simone Cavallini, Mirko Donati within the Laboratorio Ufficiale per le Esperienze dei Materiali da Costruzione, University of Pisa.

I would like to express my deep gratitude to my family for their loving support, which was of inestimable value during this path.

Finally and most importantly, I am immensely grateful to Francesca, for her daily support and encouragement, for discussions around the content of this work and for having managed the difficult job of proofreading this text, and for the wonderful time we spent together.

Ringraziamenti

Questo dottorato è stato per me un percorso di crescita e di arricchimento umano e scientifico. Per questo devo un ringraziamento a tutte le persone che con il loro impagabile contributo mi hanno permesso di raggiungere un traguardo così importante.

Desidero ringraziare, in primo luogo, i miei supervisori per l'opportunità che mi hanno offerto e per la professionalità con la quale mi hanno accompagnato in questi tre anni. L'intero lavoro non sarebbe stato possibile senza il Prof. Ing. Maurizio Froli, che ne è stato promotore e ha fornito le basi scientifiche e tecniche per affrontarlo. Mi ha dato la possibilità con questo dottorato di sviluppare le ricerche sulle strutture ibride vitree nel solco da lui tracciato negli ultimi anni, mi ha dato commenti e consigli e mi ha fornito risorse per le prove sperimentali.

Vorrei ringraziare il mio co-supervisore Dr. Paolo Cignoni (ISTI-CNR) per avermi guidato negli sviluppi della parte computazionale. Questa esperienza con lui all'interno del Visual Computing Lab dell'ISTI-CNR è stata fondamentale per la mia crescita professionale. Questo contributo ha portato una significativa innovazione nel campo dell'ingegneria strutturale. Inoltre, i risultati raggiunti non sarebbero stati possibili se non con l'aiuto del Dr. Nico Pietroni (UTS Sydney) e del Dr. Luigi Malomo (ISTI-CNR) che ringrazio vivamente.

Grazie ad amici e colleghi di Università di Pisa, del Visual Computing Lab (ISTI-CNR) e di TU Delft, dove ho trascorso il mio periodo di ricerca all'estero, per gli interessanti dibattiti multi-disciplinari e per gli spunti intorno a questo lavoro.

Vorrei ringraziare il Dr. ir. Christian Louter (TU Delft) per avermi ospitato presso la TU Delft all'interno Glass & Transparency Research Group, per i suggerimenti riguardanti lo stato dell'arte e la struttura di questa tesi, ed infine per la supervisione del lavoro incluso nel capitolo 11.

La fase sperimentale, i cui risultati sono raccolti in questa tesi, è stata possibile grazie all'assistenza del Dr. Ing. Giuseppe Chellini, e dei tecnici Michele Di Ruscio, Simone Ca-

vallini, Mirko Donati all'interno del Laboratorio Ufficiale per le Esperienze dei Materiali da Costruzione, Università di Pisa.

Vorrei ringraziare la mia famiglia per avermi amorevolmente supportato lungo questo percorso. Il vostro è un contributo inestimabile.

Il mio ringraziamento più importante va a Francesca, per avermi sostenuto e incoraggiato ogni giorno, per aver discusso con me intorno ai temi di questa tesi e per aver svolto l'arduo compito di rilettura di questo testo. E infine grazie per il tempo speciale che abbiamo passato insieme.

Summary

The constant architectural request for transparency and de-materialization of primary structures and building skins appointed glass as structural material in contemporary buildings. Structures made of glass are essential from the material usage point of view because they constitute not only a transparent and fascinating building separation but also they can bear loads. However, the design and realization of large glass structures rely on two significant requirements. The first one is to assure adequate safety levels. Theoretical formulations concerning the remaining life-time of a glass pane submitted to a given load history are very complex and their predictions can not exclude brittle failures, so are not yet reliable enough for practical purposes. As a consequence, it is always necessary to assume the occurrence of a brittle failure in one or more glass components and to design consequently the whole construction to assure a residual safety level even in those accidental scenarios. Such a result can be reached by following the principles of the Fail-Safe Design and by adopting the concept of hybridism to relieve the glass material lacks.

The second requirement is to guarantee limited rehabilitation costs in case of glass cracking. Indeed, although a fail-safe glass structure dismisses the global collapse of the construction, the only occurrence of just a single crack produces economic damages comparable to global collapses, especially for monolithic or splice-laminated glass elements, since for aesthetic and psychological reasons, cracks are not tolerable, and the complete substitution of the damaged structure is unavoidable. Based on Damage Avoidance Design, glass segmentation and reciprocal diffuse post-tensioning by steel tendons, may be implemented as a cost-saving strategy where the replacing is limited to the only collapsed elements.

Inspired by these principles, this research explores a new design concept for hybrid glass-steel post-tensioned long-span shells to tackle both requirements. This concept is established on the developmental chain of the Travi Vitree Tensegrity (TVT) structural system, introduced by Froli (Froli and Lani, 2010; Froli and Mamone, 2014) and patented by the Univer-

sity of Pisa (Froli, 2006, 2014).

Hybrid glass-metal systems are up to now limited to mono-dimensional elements (such as beams and columns) or simple bi-dimensional elements (arches, domes, barrel vaults). On the other hand, only few albeit seductive shells made of glass have been built in statically or geometrically favourable cases while; when the lattice surface is submitted to limited or diffuse positive stresses, grid shells are preferred as alternatives. In grid shells, apart from supporting its own weight, glass plays the role of simple cladding, and the load bearing function is delivered to the metal grid.

The approach proposed and discussed in this thesis is based on the collaboration of multiple laminated triangular glass panels with a filigree steel truss, which constitutes the unbonded reinforcement of each panel edge. The panels are further post-tensioned by means of cables in order to add a beneficial compressive stress on their surfaces preventing crack initiation. In the development of this challenging long spanned shells, redundancy is an essential requirement and should be designed properly in severe scenarios, accounting glass cracking. Thus, the reinforcement cross area can be sized in a performance-based design approach to support all panels supposed collapsed in the limit extreme case, defined as ‘worst case scenario’. Being unable to fulfil safely any load-bearing task, the cracked panes are considered as a dead load, approaching the grid shell behaviour.

The conceptual design phase of such shells is managed automatically using an innovative approach, developed in collaboration with the Institute of Information Science and Technologies (ISTI), National Research Council of Italy (CNR) in Pisa, that tackles geometric and manufacture constraints as well as structural requirements. The main components of the structure are thus generated starting from the remeshing of a continuous shell surface, assigned its loading and boundary conditions. The approach is able to place the cables on the shell to install a favourable static regime on the surface, exploiting the best structural feature of the glass material that is the compression strength. This automatic cable-placement capability consists in the most challenging part of the work and, at the meantime, brought to one of the most significant innovation in the state-of-the-art of pre-stressed structures and of the static-aware algorithms. In particular, such morphogenesis procedure derives an optimized cable net, with the relative pre-load, such that the traction on the resulting hybrid shell is minimized. Cables are aligned to the edges of the mesh to maximize the transparency and for constructional reasons.

The quality of the results produced and the significance of the proposed strategy is demonstrated with global nonlinear analyses produced on several datasets. The shells show good static performances, high stiffness and redundancy rate with respect to the worst case scenario. Moreover, glass panes are prevalently and almost-uniformly loaded in compression. Also visual and structural lightness are substantially improved with respect to their grid shells

competitors.

The structural behaviour of these structures is further investigated by means of analyses on a local plan to confirm their feasibility. The two most relevant components are investigated: the node and the glass panel. Experimental cyclic tests and their numerical description lead on a six-way node attest the node load-bearing capacity and stiffness, which make it suitable for the statically-relevant task assigned to it. The finite element models are generated with a Reverse Engineering procedure. Triangular laminated glass panels are a novel and un-explored research field, their Ultimate Limit State performances, in the case of in-plane and out-of-plane loading, are deduced by parametric nonlinear analyses, calibrated on the failure tests of the TVT γ prototype.

Keywords

Structural glass; Shell; Fail Safe Design; Damage Avoidance Design; Post-breakage behaviour; Post-tensioning; Hybridism; Hybrid structure; Triangular glass panel; Architectural Geometry; Computational Design; Membrane forces; Funicular; Reverse Engineering, Finite Element Model.

Sommario

La costante richiesta architettonica di trasparenza e smaterializzazione dell'involucro e delle strutture portanti ha permesso al vetro di affermarsi come materiale strutturale negli edifici contemporanei. Il progetto e la realizzazione di strutture vitree di grande impegno statico sono però legate all'ottenimento di due principali requisiti.

Il primo è di garantire adeguati livelli di sicurezza. Nonostante l'accresciuto background tecnico-scientifico in materia di valutazione della vita utile di un componente vitreo, non è possibile sottrarsi allo scenario di crisi fragile dell'elemento, soggetto a carichi di progetto o a eventi accidentali. Conseguentemente, bisogna assicurare la sussistenza di un livello di sicurezza residuo a danno avvenuto applicando i principi del Fail-Safe Design (FSD) e l'ibridismo strutturale, il quale conferisce duttilità e mitiga le negatività del vetro.

Il secondo requisito è di garantire limitati costi di riparazione nel caso il vetro si fratturi. Infatti, nonostante il collasso sia impedito se i precedenti principi FSD sono efficacemente declinati, per ragioni estetiche e psicologiche l'elemento danneggiato va comunque sostituito. Quindi, sebbene lo Stato Limite Ultimo (SLU) non sia raggiunto, le perdite economiche rilevate sono ad esso comparabili. Ispirandosi ai principi progettuali del Damage Avoidance Design (DAD) si possono adottare segmentazione e precompressione. Inoltre, in questa configurazione si ottengono benefici anche allo SLU. Con l'obiettivo di soddisfare entrambi i precedenti requisiti, nella presente ricerca si indaga un sistema strutturale ibrido vetro-acciaio per gusci sottili trasparenti a grandi luce, il quale si pone in continuità evolutiva con il sistema Travi Vitree Tensegrity (TVT), brevettato da Froli (Froli and Lani, 2010; Froli and Mamone, 2014) per l'Università di Pisa (Froli, 2006, 2014), dove i principi enunciati precedentemente sono stati già impiegati con successo.

I sistemi ibridi in vetro-acciaio finora impiegati si limitano maggiormente ad elementi monodimensionali, quali travi e colonne, o a semplici elementi bidimensionali, quali archi e sue derivazioni. Pochi gusci compressi adottano il vetro come materiale strutturale, e i pochi

casi, studiati o realizzati, si limitano a casi geometricamente e staticamente semplici. Nella pratica usuale si preferisce adottare le grid shells dove il contributo statico del pannello vitreo è nullo ad è ridotto a mero tamponamento di un grigliato metallico.

Il presente concetto strutturale si basa sulla collaborazione tra pannelli vitrei triangolari laminati e un grigliato filigraneo di aste in acciaio, le quali costituiscono gli elementi di rinforzo del vetro (o armatura, in analogia al caso del cemento armato). Inoltre, tali pannelli sono pre-compressi tramite un sistema di cavi, il cui effetto è l'innalzamento della resistenza alla fessurazione. L'aspetto della ridondanza strutturale è fondamentale in questi gusci ibride e necessita un accurata valutazione della sicurezza residua negli scenari di crisi della struttura. In particolare, si può definire una condizione detta 'worst case scenario' in cui i pannelli vitrei si considerano collassati e incapaci di portare carico. In questa condizione, unicamente il grigliato di aste può scongiurare il collasso globale. Pertanto, deve essere progettato per sostenere almeno il carico del vetro con un comportamento analogo a quello di una grid shell, anche se con un fattore di sicurezza ridotto.

La metodologia di ricerca proposta per la fase concettuale si basa sulla definizione di un processo automatizzato di generazione dei principali elementi strutturali a partire da una superficie ideale continua, assegnate le condizioni di bordo. Tale metodologia, in gradi di gestire vincoli geometrici, meccanici e costruttivi, è stata sviluppata all'ISTI - CNR di Pisa. Il posizionamento di cavi post-tesi sulla superficie rappresenta la principale opportunità di instaurare un regime statico favorevole sulla superficie, sfruttando la caratteristica peculiare del vetro, ovvero l'ottima capacità di resistenza a compressione. Nella fattispecie, l'algoritmo sviluppato è in grado di ricavare una rete di cavi ottimale, con relativi gradi di pre-trazione, tale che la trazione residua sul guscio sia minimizzata. Tali cavi sono allineati alle aste di rinforzo per motivi estetici di massimizzazione della trasparenza nonché per motivi costruttivi.

La bontà dei risultati ottenuti applicando questa metodologia a diversi casi studio è stata provata tramite analisi non lineari da cui si sono riscontrate ottime prestazioni dal punto di vista statico, alta rigidezza delle strutture e un soddisfacente gradi di ridondanza misurato rispetto al 'worst case scenario'. Inoltre, i pannelli vitrei sono prevalentemente e quasi uniformemente compressi. Confrontando i risultati con delle grid shells ricavate sulla base della stessa geometria, il grado di trasparenza e la leggerezza strutturale dei gusci ibridi risulta innalzata rispetto a tali diretti concorrenti.

A confermare la fattibilità di queste strutture, ulteriori investigazioni a livello locale hanno riguardato il comportamento meccanico di un nodo esavalente in acciaio e del pannello triangolare vitreo. Il nodo è un elemento fondamentale del sistema ed è stato testato sperimentalmente tramite test ciclici; la sua risposta statica è stata successivamente descritta tramite modelli agli elementi finiti mediante una procedura di Reverse Engineering. Il

comportamento allo Stato Limite Ultimo dei pannelli vitrei triangolari laminati è dedotto da analisi parametriche non lineari agli elementi finiti condotte per due scenari di carico, nel piano e fuori piano. Il modello è stato tarato sul comportamento a rottura del pannello del prototipo TVT γ .

Contents

Preface	iii
Acknowledgements	v
Ringraziamenti	vii
Summary	ix
Sommario	xiii
I Introduction to the research	1
1 Introduction	3
1.1 Problem definition	5
1.1.1 Background and motivation	5
1.1.2 Research proposal	6
1.2 Detailed objectives	8
1.3 Synopsis and outline of the dissertation	9
II State of the art	13
2 Use of glass in buildings	15
2.1 Introduction	17

2.2	Evolution of architectural glass	17
2.3	Glass as a structural material	20
2.3.1	Basis of design	23
2.3.2	Post-breakage behaviour	25
2.4	Summary and conclusions	25
3	Need for hybridism	27
3.1	Introduction	29
3.2	Composite glass concepts	30
3.2.1	Glass web beams with steel flanges	30
3.2.2	Segmented glass web embedded in a filigree steel structure	30
3.2.3	Hybrid columns and struts	31
3.2.4	Composite shear walls	32
3.3	Reinforced and post-tensioned glass concepts	33
3.3.1	Glass beams with bonded reinforcement	35
3.3.2	Glass beams with unbonded external tendons	36
3.3.3	Reinforced slabs and roofs	39
3.3.4	Reinforced façades	40
3.3.5	Reinforced and post-tensioned arches and vaults	40
3.4	Modular, segmented, post-tensioned glass structures: the TVT concept	43
3.5	A spatial extension of TVT concept: the SVT concept	46
3.6	Summary and conclusion	48
4	Architectural geometry of glazed lattice shell structures	51
4.1	Introduction	53
4.2	Overview of key examples from practice	54
4.3	Surface topology panelization	55
4.3.1	Triangular topology	57
4.3.2	Quadrilateral topology	58
4.3.3	Polygonal topology	59
4.4	Shell lattice structures using glass as main load bearing material	60
4.4.1	Post-tensioned triangulated dome	60
4.4.2	Barrel-vault roof of the <i>Maximilianmuseum</i>	60
4.4.3	Delft glass dome	61
4.4.4	Adhesively bonded double-curved shell dome	61
4.4.5	Plate shell structures of glass	63
4.5	Summary and conclusion	64

III	Concept and morphogenesis of reinforced and post-tensioned glass shells	67
5	Structural concept	69
5.1	Introduction	71
5.2	The safety level in addition to FSD: the DAD	71
5.2.1	Hints of DAD philosophy	72
5.3	Main principles	73
5.3.1	Hybridism and segmentation	73
5.3.2	Endogen and esogen compressive stresses	74
5.3.3	Buckling restraint	75
5.3.4	Enhancing the redundancy level by means of reinforcement	75
5.4	Conception and design features of glass shells	76
5.4.1	Conceptual design	77
5.4.2	Assembly procedure	84
5.4.3	Non-structural requirements	86
5.5	Summary and conclusions	87
6	Morphogenesis of reinforced and post-tensioned glass shells	89
6.1	Introduction	91
6.2	Basic idea and objectives	92
6.3	Assumptions	94
6.4	Methodology	96
6.4.1	Stiffness calibration of the truss elements	98
6.4.2	Model generation and settings	98
6.4.3	Linear Finite Element Analysis	100
6.4.4	Derivation of the Cable Net	100
6.4.5	Selection of optimal subset of cables	102
6.5	Implementation and results	103
6.6	Summary and conclusion	105
7	Materials	113
7.1	Introduction	115
7.2	Glass	115
7.2.1	Chemical and physical properties	115
7.2.2	Mechanical properties	115
7.2.3	Products and treatments	117
7.2.4	Design	119

7.3	Steel	120
7.4	Spacers materials	121
7.5	Other materials used in the experimental tests	122
7.6	Summary and conclusion	122
IV	Design exploration, numerical and experimental investigations	125
8	Design exploration	127
8.1	Introduction	129
8.2	Objective and methodology of global analysis	130
8.2.1	Starting geometries dataset	130
8.2.2	Design workflow	130
8.2.3	Modelling, analysis and verification methods	132
8.3	Theoretical behaviour of basic structural unit	135
8.3.1	Model generation	136
8.3.2	Results and comments	136
8.4	Results and discussion	138
8.4.1	Statics of the shells	139
8.4.2	Redundancy level with respect to the WCS	140
8.4.3	Comparison with grid shells	142
8.5	Summary and conclusion	144
9	Experimental investigation on a six-way connection	145
9.1	Introduction	147
9.2	Objective of the experiments	147
9.3	Experimental apparatus and methods	148
9.4	Specimen	151
9.4.1	Specimen and measurement technique	151
9.4.2	Survey through 3D laser scan and imperfections estimation	152
9.5	Results and evaluation	156
9.6	Summary and conclusions	157
10	Numerical modelling of the node and comparisons with experiments	167
10.1	Introduction	169
10.2	Objective of numerical investigations	170
10.3	Modelling strategy and analysis	170
10.3.1	FEM generation	170
10.3.2	AD model	171

10.3.3	RE model	171
10.3.4	WB model	172
10.3.5	Analysis settings and materials	172
10.4	Result and discussion	173
10.4.1	AD model	173
10.4.2	RE model	174
10.4.3	WB model	175
10.5	Summary and conclusions	175
11	Parametric numerical investigation on triangular laminated glass panels	177
11.1	Introduction	179
11.2	Objective of numerical investigations	179
11.3	Parameters and method	179
11.3.1	TVT γ panel behaviour and model calibration	184
11.4	Modelling strategy and analysis	185
11.5	Result and discussion	187
11.5.1	In-plane loading case	188
11.5.2	Out-of-plane loading case	192
11.6	Summary and conclusions	194
V	Integrated discussion, conclusions and recommendations	197
12	Discussion and conclusion	199
12.1	Discussion	201
12.1.1	Structural concept	201
12.1.2	Computational and geometry aspects	203
12.1.3	Elements performances	204
12.2	Conclusions	204
13	Recommendations	207
13.1	Introduction	209
13.2	Base geometry selection and topology	209
13.3	Post-tensioning paths	210
13.4	Details design	210
13.5	Assessment of structural performances	212
13.6	Assembly and other requirements	212
13.7	Future research directions	213

VI Appendices	215
A Nonlinear global analyses results	217
A.1 Load step comparison for the hybrid post-tensioned case	219
A.1.1 Tetrahelix	220
A.1.2 Sphere	222
A.1.3 Simplilium	224
A.1.4 Vault	226
A.1.5 Bean	228
A.1.6 Calla	230
A.1.7 Snake	232
A.1.8 Donut	234
A.1.9 Triangle	236
A.2 Principal stress σ_{22}	239
A.3 Comparison with the WCS case at the ULS	245
B Photos of the node and the testing phase	251
C Drawings of the specimen and the test	257
D Comparison of experimental and numerical node results	265
D.1 Comparison of experimental anti-polar readings	267
D.2 Numerical results of AD model	269
D.3 Numerical results of RE model	273
D.4 Numerical results of WB model	277
D.5 Comparison of AD and RE numerical results	281
List of Figures	285
List of Tables	292
Acronyms	295
Bibliography	297
Curriculum Vitae	307