ABSTRACT:

The form of an object is a direct representation of the forces by which it has been subjected; forces both internal and external. As forms in nature, like those of the built environment, are subject both to the limitations of the materials strength and external forces such as gravity, lessons from nature are often applicable to the built environment, providing useful insights into new techniques for advancements in structural efficiency. The philosophy of biomimicry has significant potential in the structural realm, whereby rather than simply copying the forms of nature which can be problematic due scales of magnitude, the true profundities are believed to come from an improved understanding of how nature and its forms work. Orchids are the specific focus of this study as the diverse and varied forms often overcome external forces through a manipulation of form. To resist force through form, rather than ‘the awkward accumulation of matter,’ is the core by which structural efficiency is founded. The thesis provides a general overview into the aspects of: sustainability; biomimicry; structural efficiency; the developments and opportunities presented by material and computer-aided design advancements, as well as researching the forms developed by the great structural artists such as; Antoni Gaudi; Eduardo Torroja; Eladio Dieste and Felix Candella. A variety of orchid forms were selected and analysed, and the findings are presented as common structural techniques and forms seen throughout a number of the orchid species. It was found that many of the orchid forms share similarities with those of the structural artists, although the great diversity of forms presents new techniques which could have exciting implications on the next generation of structures.

Keywords: Biomimicry, Computer-Aided Design, Orchids, Structural Efficiency
INTRODUCTION

“Certain modern artists and engineers are making more and more specific use of light structures which resemble, in form, shells and other elements of nature. These forms, some of which are warped, are obviously going to play an increasingly important role in the future. We cannot continue to construct our cities limiting ourselves to edifices exactly like boxes, exclusively inspired by the systems of the slab and the pillar. In the continuous evolution of modern architecture, it is more than likely that Gaudi’s last experiments will acquire increasing value and will be more fully appreciated. Then his importance as a pioneer and a prophet will be acknowledged.” Jose Luis Sert (1955) (Descharnes 1971:15)

Sustainability is unequivocally the most pressing issue of our time. The recently emerging philosophy of biomimicry represents a highly plausible guideline for humanity to address sustainable development, through innovation, guided by wisdom. A guiding principle of biomimicry is the idea of ‘tapping the power of limits.’ This principle is pertinent for the purpose of this thesis, as this is also the core principle by which structural artists discover their genius. Furthermore, it is apparent that structures in nature, are subject to the same forces as the built environment, and thus the idea of applying the philosophy of biomimicry to structural innovation could provide great insight. Forms in nature are derived from the forces by which they are or have been subjected. In contrast, the built environment tends towards pre-determined forms such as flat planes, which due to their inefficiencies are compensated through mass or the addition of supporting members. In this regard, architect Antoni Gaudi was well before his time. Gaudi looked to nature as his mentor, and his building forms, like nature were derived from the forces acting upon them. Through the intelligent use of form, Gaudi provided resistance to the acting forces, subjecting his materials to high levels of force within their capabilities achieving great structural efficiency.
Structural efficiency is important not only economically, but is also critical in creating more sustainable designs. As evident in the work of Gaudi as well as other structural artists such as Torroja, Dieste and Candella, structurally efficient forms, in following the laws of nature tend to result in elegant and beautiful forms. This thesis, whilst not of a mathematical or technical nature, explores structural principles and the influence of form on structural efficiency. The thesis provides a general overview of sustainability, biomimicry, structural efficiency and the various innovations of the aforementioned masters. The research then explores the forms of nature, specifically orchids, to analyse their curves for structural merit, discovering new forms which could become applicable in the built environment. The success of structural artists relies on their development of economical solutions that are easily constructed, for example, through the use of straight-line generators. As computer-aided design and manufacturing continue to advance, the possibility of forms with greater complexity will be made increasingly feasible and therefore lessons from nature increasingly applicable.

1. 1. SUSTAINABILITY AND THE ORIGINS OF BIOMIMICRY

1.1. Sustainability

Sustainability and sustainable development are terms both used widely today, but as Palmer (1997: pp.87) argues, both lack any overall consensus, and thus their meanings are lost under ambiguities between different parties. Whilst the term is understood in its generality, the holistic nature of the term lends it to favour different priorities for different people. The environment has always been at the core of sustainability, championed by the ecology movement, although over time its definition has been broadened to place a greater focus on humanity which had been historically absent in the ecology movements priorities. The ecology movement might argue that the relationship between humanity and the environment is intrinsic and thus by caring for the environment they are indirectly caring for humanity. Nonetheless, the definition of sustainability has become more explicit in its human focus, as Gordon Mitchell et al. highlights (Palmer 1997: pp.88), major literatures on the subject have considered sustainability to also encompass the principles of; Futurity; Equity and Public Participation.
Today sustainability is often used interchangeably with sustainable development, despite some critics such as David Pearce (Palmer: pp.87) arguing that the latter is an oxymoron. This alternate use between the two has no doubt affected the general understanding of the terms and has perhaps contributed to the meaning of sustainability being broadened. The most widely used definition for Sustainable development comes from Dr. Gro Harlem Brundtland, defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” This definition introduces the generality of sustainability,
although remains rather vague and some assumptions must be made. Despite being weak the definition does introduces the first principle; futurity. Another principle recognised to have growing importance to sustainability is that of equity. In an age of nuclear armaments, the importance of peace is significant to both humanity and the future of the planet. The Friends of the Earth Scotland (Palmer: pp.90) recognise that in a finite planet, with finite resources, greater equity is pivotal to maintaining peace. The last principle; Public Participation came from the Rio Declaration on Environment and Development (UNCED, 1992) and recognises the fundamental necessity for all to be involved in our quest towards sustainability. The four principles recognised by Mitchell are intrinsically linked and are all critical in our path towards sustainability. Palmer has devised a scale, to aid people or organisations to make clear their position or understanding of the term, as to avoid miscommunication. For the purpose of this thesis, any reference to sustainability will be in regard to environmental management and environmental degradation as fig. 2 indicates the authors weighting. Whilst the author appreciates that these principles are all important and intrinsically linked, reference to equity and public participation will be made apparent through the use of alternate words.

1.2. Context

There is a growing concern that we are fast approaching or have already surpassed the limits to which our planet can sustain (Enrlich 1997: pp. 153). The stress on our planet has been driven by a minority, in which 20 per cent of the world’s population consume 80 per cent of the world’s resources (Enrlich 1997: pp. 157). The rapid development of the remaining 80 per cent of the world’s population is believed by Murphy et al. (1997: pp. 173) and Watson (Woodruffs 2008: quoted in China: from red to green) to be the potential tipping point for the future of humanity. As Enrlich (1997) highlights, this is of real concern, as ‘the poor plan and aspire to consume as the rich do.’ Compounding these problems is a growing population projected to expand to 9.2 billion people by 2050 (Population Division 2007: pp. vii). Benyus (1996: pp. 251) highlights that the human enterprise functions as a Type I species, also known as an opportunist, whereby the species sprouts to makes the most of abundance, but soon after the boom, Type I species follow bust. She explains that in the past when depleting an eco-system, humanity could expand to virgin land and thus the opportunist was supported. The difference now, she argues, is that for the first time in history few virgin lands remain (Benyus 1996: pp. 251) and the poor are often already subjected to marginal lands. It is clear that humanity needs a new paradigm if it is to realise sustainability and comfortable living conditions for all. The direction we should take is widely debated and two prevalent schools of thought have emerged over the past decades.

1.3. Schools of Thought

The first school of thought, accepts the idea of natural limits, placing emphasis on a critical assessment between needs and wants and thus advocating against consumerism and the capitalist mentality. In this view, society needs to reprioritise its values, leading to a cultural shift, with a focus on ‘the simple life’ and supported by the use of low-technological solutions. This school of thought has been championed by philosophers such as Mohandas Gandhi (1869-1948), and Henry David Thoreau (1817-1862) (Avery 2007: pp.85-94). Williams (1974: pp.
181) highlights the challenge, that to follow this path ‘we would be the first human society to impose a purposeful self-discipline,’ which is in direct opposition to the persuading tide of capitalism. The competing school of thought is founded on a deep faith for technology and human innovation to overcome all obstacles, championing commerce as ‘the driver of change.’ (Woodruff 2008: McDonough quoted in China: from red to green). According to Faucheux and O’Conner ‘the conflict between advocates of weak sustainability and of strong sustainability is founded...on a divergence in the confidence placed in technical change’ (Palmer et.al 1997: pp. 81). This appears to be a plausible assessment. Those who have the utmost faith in technology are unlikely to accept the notion of natural limits, as historically, innovation has shown that these can be overcome. This faith in innovation therefore justifies a reluctance to take responsibility or change poor habits. The danger of this mentality, as Einstein pointed out, is that ‘a problem cannot be solved by the same amount of thought which created it’ (French 1988: pp. 247), and thus it appears a dangerous game as humanity continues to distance itself further from nature and challenges continue to surmount. A recently emerging philosophy growing significant support is Biomimicry. Biomimicry combines the fundamental aspects of the two schools of thoughts promoting innovation as an inevitable player towards sustainability, although an underlying wisdom remains at the core, calling for humanity to establish a more humble position on our planet.

1.4. Origins of Biomimicry

‘Unlike the Industrial Revolution, the Biomimicry Revolution introduces an era based not on what we can extract from nature, but on what we can learn from her (Benyus 1996: pp. 2).’

Biomimicry is defined as follows;

BI – O – MIM – IC – RY
[From the Greek bios, life, and mimesis, imitation]

1. *Nature as model*. Biomimicry is a new science that studies nature’s models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf.

2. *Nature as measure*. Biomimicry uses an ecological standard to judge the “rightness” of our innovations. After 3.8 billion years of evolution, nature has learned: What works. What is appropriate. What lasts.

3. *Nature as mentor*. Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but on what we can learn from it. (Benyus 1996: preface)

Whilst the idea of taking inspiration from nature as our guide is far from new, as quite pertinently expressed by Leonardo da Vinci (1452-1519) many hundreds of years ago, stating that “those who take for their standard any one but nature-the mistress of all masters-weary themselves in vain,” (Vezzosi 1997: pp.138, originally from Codex Atlanticus) the growing interest and discoveries in biology continues to expand our appreciation for nature. Biomimicry is the premise that nature represents a blueprint to survival, as Darwin had earlier alluded in his hypothesis; ‘survival of the fittest.’ Over millions of years, nature has evolved and the species...
that exist today are the champions of survival. As Benyus (1996: pp. 4) states these survivors have been ‘imaginative by necessity’, having already ‘solved the problems we are struggling to solve.’ Nature as model, measure and mentor, firstly lays impetus on our path towards sustainability through innovation. Secondly it calls for humanity to consider nature and its harmonious closed-loop systems. How do things relate and thus how can we relate? Lastly, biomimicry demands from us, greater respect for nature. Humanity can no longer consider nature and its limits at odds to our aspirations, but they must be seen as one and the same. Benyus suggests, the time is now, that ‘we adapt to the earth rather than the other way around’ (1997: pp. 7). Biomimicry also calls for greater efforts to safeguard nature’s creations, for obvious reasons. Benyus warns of ‘the very real possibility of losing a quarter of all species in the next thirty years (Benyus 1997: pp. 9). In our quest towards sustainability Biomimicry appears likely to play a growing role in all facets, but particularly the built environment.

1. **BIOMIMICRY AND THE BUILT ENVIRONMENT**

2.1. The role of built environment and structural efficiency on sustainability

It is estimates that the built environment accounts for roughly 40% of energy consumption and 50% of greenhouse gas emissions (Woodruff, 2008). This, in combined with the construction sectors influence on material extraction and consumption, is likely to substantiate the built environment as the single greatest influence on sustainability. Webster (2004, pp. 181) highlights the significant role of structural systems within the built environment, which he states ‘account for more than one-third of the material use and waste generation and more than 10% of the energy use and greenhouse gas production over a building lifespan of 50 years’ (2004, pp. 181). Whilst Webster acknowledges structural systems currently play a lesser role to the energy use over the life of the building, with the advent of renewable technologies, he suggests, the overall significance of structural systems will inevitably grow by comparison. Furthermore, the developments of renewable energy and technologies are largely beyond the influence of architects and structural engineers and considering the holistic nature of sustainability, advancements will be needed in all aspects of the built environment.

At present structural systems tend to be largely predetermined, following straight lines and flat planes, which the construction industry has long focused its efforts. Eladio Dieste (1917-2000) was critical of this often indiscriminate selection as he states it ‘does not make use of materials in any rational way’ (Anderson 2004: pp. 184). As Ochsendorf (Anderson 2004: pp. 95) makes pertinently clear as seen in Fig.3, to hold a flat piece of paper out in a horizontal plane, one will quickly appreciate its poor resistance to bending and it will flop accordingly (a). In contrast, by providing the plane with a curve or fold, despite its same thinness, it gains significant strength and stability and can resist the bending forces with ease, thus highlighting the power of form (b). Hartley (1993: pp. 1) highlights that to overcome structural inefficiencies such as those found in flat planes ‘traditional industrial technology has always depended on sheer volume of resources to overwhelm problems’ or the addition of supporting members. As the global economy evolves to consider environmental costs, and resources become increasingly scarce and commensurately more expensive, structurally efficient forms will become increasingly
favourable. Eugene Tsui (1954-) suggests that built forms should not be so regimentally predetermined in shape (such as the box) whereby we ‘then try to negotiate forces acting on that shape,’ rather he suggests we learn from nature’s example where ‘the shape is determined by the forces that act upon it’ (Tsui 1999: pp. 39).

![Image](image_url)

**Fig. 3** The influence of curvature in membranes: a) without curvature, and b) with curvature. Source: John A. Ochsendorf from (Anderson 2004: pp. 95)

### 2.2. Form in Nature

Benyus states that ‘organisms have evolved to work smarter, not harder (Benyus 1997: pp. 5), with their forms synonymous with their function and often further economised by combining one structure to serve multiple functions (Benyus 1997: pp. 265). The reason for nature using materials and energy sparingly, as Benyus explains is a matter of survival (Benyus 1997: pp. 5) whereby through the power of limits, nature ‘optimises rather than maximises’ (Benyus 1997: pp. 4). She highlights that species ‘build for durability, but they don’t overbuild’ and nature also benefits through the use of composite materials to gain strength rather than bulk (Benyus 1997: pp. 265).

Thompson (1917: pp. 11) hypothesises that ‘the form of an object is a ‘diagram of forces.’ He further explains that the form of an organism is both the result of internal and external forces by which it is and has been subjected. The form is affected internally by the phenomenon of growth, whereby materials will be redistributed, at varying rates to different parts. Externally the form is influenced and resisted by forces such as surface-tension and gravity (1917: pp. 53). Thompson states; ‘we know, as a fundamental theorem of dynamics that the potential energy of a system tends to a minimum and in that minimum finds, as a matter of course, its stable equilibrium’(1917: pp. 208), or structural stability as the phenomenon is known in the building sector. Thus an objects form will find a balance between internal and external forces. For ‘minute organisms, or the small cellular elements of larger organisms’ Thompson explains their forms ‘will be governed by surface-tension; while the general forms of larger organisms will be due to other non-molecular forces,’ (1917: pp. 215) such as gravity. It is therefore plausible to hypothesise that the forms of orchids are influenced by surface-tensions at the molecular level,
although their overall form is more the resulting affect of gravity. As Thompson states ‘gravity not only controls the actions but also influences the forms of all save the least of organisms,’ and thus forms in nature share the same major limitation as the built environment and therefore provide direct relevance as mentors.

Whilst the forms in nature provide a plethora of structural inspiration, the reader must appreciate as Tsui warns that ‘one cannot simply take a chosen form and attempt to enlarge or reduce it without dangerous consequence’ (Tsui 2007: pp. 21). The reason for this as Tsui and Thompson both highlight is a phenomenon known as scales of magnitude, whereby the rate by which volumes increase in comparison to linear dimensions and areas is significantly greater. For example, if a form is at a scale of 1:1, with a linear dimension of one, a surface area of one and a volume of one, the relationship between how these grow when the form is enlarged become exponentially different. If the form was increased by a factor of eight, so that its scale is 8:1, its linear length becomes eight, its area becomes 64 and its volume explodes to 512. The more one enlarged the form, the greater the disparity becomes between its linear dimensions, area and volume. So although by enlarging a form, the cross-section of the form is enlarged accordingly, perhaps suggestive that the relationship is unaltered, in reality the relationship between internal strength and external forces by which it was originally formed has been changed significantly. To maintain this relationship; the stable equilibrium, the material strength would also have to increase by the same factor by which the form is enlarged.

Thompson highlights that this phenomenon limits the size in which hollow shells in nature occur as ‘the stresses within which increase much faster than the mere scale of size, every hollow structure, every dome or cylinder, grows weaker as it grows larger’ (1917: pp. 33). Apart from using stronger materials, Tsui suggests we can further overcome the limits of scale by using materials in more economical ways, following even more closely the stresses by which the structure is exposed, adding and subtracting mass where appropriate, as seen in the forms of bones (Tsui 2007: pp. 23). The greatest developments in structural efficiency will come from learning from nature rather than imitating her and by acknowledging this; Antoni Gaudi was well before his time.

2.4. Precedents of Biomimicry in Architecture

What becomes retrospectively apparent as our knowledge of nature continues to expand is that many of mankind’s greatest innovations had already existed in nature in some regard. In fact, those by whom we hold the highest esteem for their contributions to human knowledge were often those who simply had the profound insight to understand the very workings of nature, for this is the basis of science. In architecture, Gaudi’s appreciation for geometry and engineering allowed him to quickly discover deeper profundities in nature, beyond the mere superficialities. He was thus able to express principles, rather than merely imitate nature’s effects.

One geometrical phenomenon found frequently in nature appreciated and used by Gaudi was that of the Helicoid. Charles Darwin in observing the regularity by which certain climbers span around a stem (Fig. 4) hypothesised that “the stem probably gains rigidity by being twisted (on the same principle that a much twisted rope is stiffer than a slackly twisted one), and is thus indirectly benefited so as to be able to pass over inequalities in its spiral ascent, and able to carry its own weight when allowed to revolve freely.” (Thompson 1917, pp. 625)
Gaudi appreciated that through this torsion, helicoids gain strength and he therefore adopted the form to be used in many of his spiral staircases such as in the towers of the Sagrada Familia Cathedral as seen in Fig.5. Furthermore, the helicoid form is produced using ruled surfaces or from straight-lines generators and thus the form was economical and practical to construct. The use of ruled surfaces was a favoured practice of Gaudi and was also adopted widely by the structural artists who followed. As Timothy Becker highlights its use ‘not only imbues the vaults with grace but also creates forms on demand and with ease, with sound structural properties like those found in nature’ (Anderson 2004: pp. 206).

Fig. 4 Helicoidal growth of climber

Fig. 5 Gaudi’s use of the Helicoidal form
Contemporary architect, Santiago Calatrava (1951–), like Gaudi, shares a deep fascination for geometry and engineering and turns to nature for inspiration in the development of his forms. Calatrava’s guiding ‘motto “Natura mater et magistra” – nature is both, mother and teacher’ (Tzonis 1999: pp. i), is indicative of Calatrava’s reverence for nature. First created by Gaudi, columns inspired by trees are also often used by Calatrava, the form and arrangement of members elevate the column to play an active role (Descharnes 1971: pp. 15) and thus makes the materials work harder and therefore collectively gains greater structural efficiency. A great deal of Calatrava’s work also takes inspiration from bones and skeletons and a common feature in his work is the adoption of the principle of recurrence. Recurrence is the phenomenon whereby forms such as trees are thicker at the base and taper at the crown where the stresses from dead weight diminish as too the bending moments. Calatrava’s states that ‘to me, there are two overriding principles to be found in nature which are most appropriate for building: one is the optimal use of materials; the other is the capacity of organisms to change shape, to grow, and to move’ (Tzonis 1999: pp. i). Calatrava’s interest in dynamism is reflective of our age, where technology is making it quite plausible for buildings to break the shackles of statics. This appears an inevitably direction for architecture and is likely to be developed with great interest in the coming decades.

![Fig. 6 Dynamic appearance of Quadracci Pavillion Source: http://www.dingmanphoto.com/](http://www.dingmanphoto.com/)

1. **STRUCTURAL EFFICIENCY**

3.1. **Definition and key developments**

French states that ‘nearly always it is desirable to use as little materials as possible both for reasons of economy, which apply no less in nature than in human affairs, and also usually for functional reasons’(1988: pp. 105). With two decades passed since this statement, one would certainly also add to the list, the benefits towards sustainability. Historically, it was prevalent
for structures to function in compression with the use of mass materials such as stone, masonry and concrete. In Spain Catalan tiles were used to great effect, as one of the first major development towards light-weight structures. Catalan tiles are structurally effective by the manner in which the tiles overlap one another, thus acting as a shell and working as a whole, eliminating abrupt interfaces and potential weaknesses, a phenomenon found commonly in nature (French 1988, p.117). This material was used by Gaudi to great success, whereby he explored the implications of form on a structures ability to resist forces. With the advent of steel, a material which exhibits a great strength to weight ratio and impressive tensile strength characteristics, a new age in structural efficiency was born, allowing light-weight structures capable of spanning great distances. As the dead-load of a structure often accounts for a major aspect of the forces it must resist, lighter structures can provide clear advantages, often reducing both: the lateral thrusts; the vertical structure requirements and the size of footings. Garlock et al. (2009: pp.42) explains that enthusiasm for structural efficiency sprouted as ‘the spirit of rationality was popularised by Viollet-le-Duc giving it a theoretical justification. The innovation of the composite material; reinforced concrete was equally radical as that of steel, with steel and concrete in combination exhibiting greater capabilities then the materials are capable alone. Reinforced concrete with its ability to absorb tensile stresses due to the steel reinforcing and the plasticity that comes from concrete, allowed designer’s great new freedom in form.

Despite the many advantages for structural efficiency Remo Pedreschi highlights that from an engineer’s perspective, ‘we always find that the most magnificent forms are resistant to simple analysis, and we will have to do a quite a bit of simple analysis before we can achieve the most sensible and responsible way to calculate these structures’ (Anderson 2008: pp. 141). Dr. Werner Sobek, Engineer and Architect, states that “to design minimal weight structures, for engineers, is one of the most difficult things to do” (Woodruff 2008). The added complexity often associated both in designing, calculating and constructing the complex structurally efficient forms lends rectilinear forms to remain most prevalent, despite their inefficiencies. In nature an increase in complexity is a process of evolution, evolving from simple to more complex forms over time (Thompson 1917: pp.217) towards continual improvements. Despite the added complexity associated with curved forms in the built environment, as biologists refer in nature, ‘successful body designs and behaviours must be high in information content,’ (Benyus, 1996: p.274) a key to survival and suited directly to function and place. As mankind continue’s to press the earth’s limits, the importance to develop more structurally efficient forms and forms better suited to place and function, is critical as a matter of our survival. An emphasis on intelligence and quality rather than production is a characteristic of stable and mature systems in nature (Benyus, 1996: p.96) and needs to be the path we follow. Advancements in computer software will aid the designer and engineer in unravelling the complexity although the intuition of structures from the designer will remain paramount.

Structural efficiency is achieved by making the materials ‘work as hard as possible’ (Anderson 2008: pp. 141), within parameters of safety, achieved by ‘aligning the elements of a structure along lines of force’(Anderson 2008: pp. 74). Apart from achieving great economy and being environmentally sensible, Dieste appreciates that this pursuit is also conducive to producing beautiful forms.
Rowland Mainstone has developed three criteria he believes to be important in the development of new structural forms. These are as follows:

i. Intuitions of structural behaviour: a spatial awareness of stability and the geometry of structures, and a feel for the nature of the forces in a structure; a muscular, physical sense of structure.

ii. Intuitions of structural action: a more refined view of structural behaviour, the basis of the mathematical analysis of structure; the description of behaviour in the quantitative terms of forces and moments, stresses and strains

iii. Intuitions of structural adequacy: a quasi–empirical view of structures, based on experience and practise.

(Anderson, 2004: p.138)
The latter two are beyond the scope of this thesis, with intuitions of structural behaviour the primary focus for this work.

3.2. The influence of form

ARCHES

Materials commonly used in the past such as stone and masonry are poor in tension and therefore the arch which works in pure compression allowed these materials to span over spaces. The laws of physics permit that materials will seek equilibrium by finding their lowest point of resistance, and thus the arch due to the influence of gravity will create downward and lateral thrusts which need to be resisted for the arch to maintain its shape. If the lateral thrusts from the arch are not resisted, the funicular shape, which is the most efficient form for an arch will be lost and the form will act rather as a curved beam, taking on bending, which was absent in the funicular form (Torroja 1962: p.88). A funicular curve is one which is exhibited by holding a chain at two ends. In the example of the chain the curve acts in tension. The arch is therefore this shape reversed curving towards the sky to act in compression. The catenary curve is most efficient funicular shape for an arch of equal thickness acting only under its dead weight (Torroja 1962: p.90) but as Torroja highlights heavier materials tend to demand higher curves as to reduce the magnitude of lateral thrusts which could become excessive (Torroja 1962: p.89). The lower the funicular profile of the curve, the higher the compressive forces and the greater the lateral thrusts. Traditionally lateral thrusts were absorbed by massive walls or buttresses or in the case of vaults which act like a series of arches, the vaults were often placed beside one another to counter one another’s thrusts. For Gaudi the addition of lateral supports was seen to be a structural flaw and he sought to discover an arch form which required no additional lateral support. His experimentations and use of graphic statics allowed him to align the thrusts with the supporting columns (Anderson 2004: p.71) and he was able to merge the columns seamlessly into the arch form developing what Descharnes et. al (1971: p.54) describe as an ‘oblique parabolic order’.

Anderson (p.140) highlights that for arches the greater part of the stresses are due to its own dead weight and therefore can benefit significantly from lighter materials. Lighter materials therefore allow lower funicular profiles with greater spans more feasible as the reduced lateral thrusts can be absorbed by steel ties acting in tension between the arch ends or through modest
lateral supports. Whilst the case, like Gaudi, the structural artists that followed viewed these additional supports as a structural flaw and sought to overcome forces through form alone.

**SHELL STRUCTURES**

Like arches, the deadweight tends to produce the greatest stresses in shell structures, especially in roofing applications. Like arches a lighter profile therefore becomes beneficial to the structure as it must withstand less force and can therefore span greater distances. Garlock (2009) describes the remarkable phenomenon of shell structures, stating: ‘it may seem counterintuitive that thinner structures when properly formed can lead to surfaces with lower stresses, but this is a structural truth discovered in the late 1920s by Robert Maillart.’

Whilst the case, as the shell becomes lighter the risks of buckling will increase commensurately. The addition of bulk or the use of stiffening ribs can satisfy this problem although for structural artists both provide inadequate solutions. For structural artists the risks of buckling can be overcome through the use of form alone, namely through the use of double-curvature, which provides the form with the necessary rigidity. The stresses in shells tend to be significantly more complex than arches or vaults and with double-curvature this becomes increasingly apparent. In Candela and Dieste’s shells they sought optimum efficiency with the objective to create what Garlock et. al described as ‘a proper shell,’ whereby the shell functions according to the membrane theory. The membrane theory is where the forces (compression or tension) are carried in uniform throughout the thickness of the shell without any bending, made possible by the shells correct geometry (Garlock et. al, 2009: p.77). In an appropriately designed shell, the structure will work according to the membrane theory whereby an unevenly distributed load will be spread across the thin shell surface. The result is a form of great structural efficiency as large loads are resisted by a thin shell. Often with shell design the most problematic areas whereby tensile stresses will be greatest is where the shells connects its supports and it is common for additional reinforcing to be located at these articulations (Garlock et. al, 2009: p.123). Specific examples of shells will now be discussed in relation to the innovations of key structural artists.

### 3.3. Structural Artists – Gaudi, Torroja, Dieste and Candela – from straight-lines to curves

**GENERAL INTRODUCTION**

Structural artists are those who have dedicated their working lives towards the pursuit of structural perfection. It is common as Anderson (2004: p.94) highlights for a structural artist to concentrate on one specific material and extend the materials known capabilities. Whilst the methodology of structural artist’s such as Gaudi, Torroja, Dieste and Candela varied, what they all shared was an intimate understanding of the construction processes, a sound understanding of structural behaviour and an artistic discrimination, which allowed their structures to be elevated to works of art. A view shared by Torroja, Dieste and Candela and earlier touched on by Mainstone’s three aspects of structural innovation is the importance in which intuition plays on the development of structurally efficient forms. Dieste for example, was quite critical of the education of engineers, whereby he believed students were exposed to mathematical formulas
and computer modelling but failed to gain a true understanding of structural principles. As Torroja states;

“Complex and abstruse mathematical calculations are not alone sufficient to lead to conception of a structure or to guide the hand in tracing its outline: intimate and intuitive comprehension of its working forms is also needed” (Torroja 1962: p.8).

Intuition, was particular emphasised by Candela whereby in his work he generally avoided complex calculations, favouring more simple formula supported by his sound understanding of the forces at work (Garlock et. Al 2009).

A remarkable aspect in the work of structural artists, apart from the beautiful and elegant forms created, is the economic credentials of their structures in comparison to the more conventional alternatives. The economy of these structures was achieved through the efficient use of materials, often the replication of forms and formwork and their constructability, often adopting forms generated from straight-line generators to create great complexity.

GAUDI

QUADRATIC RULED SURFACES

As earlier stated the use of ruled surfaces was a favourite practice of Gaudi. One of Gaudi’s best examples was the sinuous curved roof of the schoolhouse adjacent to Sagrada Familia as seen in Fig. 7. It is apparent that the structure had a great influence on Dieste as seen in figure.8. From the central beam of Gaudi’s roof outward the form was taken by Dieste for the walls in the Church of Christ the Workers, both adjusting the orientation of the line generators to create undulating parabolic curves. In both, the sinuous curves provide the forms with rigidity reducing bending by the deep profiles in the roof and providing lateral stiffness in Dieste’s walls. Ingeniously Dieste’s undulating wall follows as Ochsendorf highlights the ‘moment diagram for a pin-supported portal frame under its own weight and therefore provides for an efficient use of materials’ (Anderson, 2004: 98) as seen in Fig. 9. The undulations of walls to resist lateral thrusts were also used in Gaudi’s schoolhouse although his undulations remain vertical rather than tilting back and forth. The undulating walls cleverly align with the troughs and peaks of the roof structure to act as tympanum, which perhaps allow the forces to be spread more evenly across the roof surface rather than favouring the valleys.
Gaudi’s schoolhouse adjacent to Sagrada Familia. Source: (Garlock et. Al 2009)

Fig.7

Fig.8 Dieste (Anderson: 74)
Gaudi also used ruled surfaces also for the generation of hyperbolic paraboloids which was to be another form highly influential to his predecessors.

**TORROJA**

The material which Torroja focused much of his efforts was reinforced concrete. A major development by Torroja according to Garlock et. Al (2009: p.45) was the realisation of the connection ‘between the stresses in a shell and the reinforcing that needed to be placed in it.’ Torroja was thus able to create smooth shells not visually expressive of the forces. The freedom to add reinforcing locally and directionally, as well as the freedom to shape reinforced concrete to the desired form to resist the subjecting forces was an aspect that made the material especially favourable for Torroja. As Torroja comments ‘unlike rolled steel, concrete is not available in definite shapes listed in a catalogue; its forms and dimensions must be designed’ (Torroja, 1962: p.58) providing a designer with great freedom. Reinforced concretes ability both in compression and tension, also makes it economical for members which must resist both as ‘the system needs to be designed to withstand what the material is weakest’ (Thompson, 1917: p.676). One of Torroja’s most notable designs the Madrid Hippodrome as seen in Fig.10 and Fig.11, which adopts the hyperbolic paraboloid, a form used by Gaudi and was later extensively used by Candella.
HYPERBOLIC PARABALOIDS

Hyperbolic Parabaloids or Hypars are generated by two paraboloids intersecting perpendicular at their centre, with their curves facing opposite directions as seen in Fig.11, creating an arch in one direction and a cable in the other. A major advantage of hyperbolic paraboloids is that the complex double curving form is constructed from straight-line generators, allowing great economy in construction, whereby conventional straight boards can be used for formwork. As Candela concluded “of all the shapes we can give to the shell, the easiest and most practical to build is the hyperbolic paraboloid” (Garlock et. Al, p. 138). Furthermore, the double curvature provides great depth in form allowing hypars to be resistant to bending. With the cable acting in tension and the arch acting in compression (Anderson, 2004: p. 42) the opposing phenomenon’s work effectively together to maintain a stable form, providing stiffness as the two attempt to flatten against the resistance of the other. In Torroja’s Madrid Hippodrome as seen in Fig.12 he takes full advantage of this phenomenon allowing the cable to cantilever over the grandstand acting as a beam as the force is channelled to the vaults, while the arch takes the load to the columns. The way by which Torroja balances the structure is quite ingenious with the roof form extending not quite as far in opposite direction but balanced through a tie, which connects to the weight of the betting hall arch stabilising one another while the arch of the stand acts as a flying buttress to balance the whole structure. If one considers the Hyperbolic Paraboloid in elevation one will also notice that the depth of the form is widest in the centre where the two paraboloids cross. This together with the upward curve makes the form ideal for cantilevering, as the wider centre which takes the force continuously narrows as it cantilevers outward in the same manner as the recurrence found in a tree, following the pattern of bending moments. Torroja further enhanced this phenomenon by reducing the section of the structure as it approaches its end where forces from dead-weight are lowest.
Hypars were also widely used by Candela and was the chosen form for the Cosmic Rays Laboratory, which as a functional requirement demanded an extremely thin shell. The extreme thinness (5/8ths of an inch) of the shell significantly increased the risks of buckling. The hypars were therefore justified as the double-curvature would provide the necessary stiffness, achieved through form rather than mass. According to Garlock et. al in his quest to simplify calculations, Candella assumed the characteristics of a single curvature barrel shell, appreciating that the hypar would at minimum, act at least as equally well. Whilst Candella’s assumption was correct it should be noted that the forces in the two types of shells are distributed quite differently. As
Faber highlights as seen in Fig.13 a barrel shell distributes the forces essentially in the same manner as a row of arches down its curve. A hyper on the other hand will distribute its forces in an oblique manner generally along the straight-line generators (p.91) and as force follow stiffness; the force is transmitted to the stiffer arches as explained in greater detail below.

![Fig.13 Distribution of forces in the barrel vault compared to the hyperbolic paraboloid. Source: (Garlock et. al, 2009: p.91)](image)

An article which was quite influential on Candella according to Garlock et al., written by K. W. Johansen ‘described how to analyse long cylindrical vaults, by treating them as beams with a circular cross-section (p. 65).’ If the same understanding is applied to the hyperbolic paraboloid, one can appreciate the advantages that come from the intersecting curves, which provides great stiffness allowing it to act similarly to a beam in both directions. As the greater depth of an ‘I’ beam provides it with greater resistance against bending, the same is true of the hyper and is why it is an effective form for cantilevers.

**DIESTE**

Born in Uruguay, Eladio Dieste focused on the development of the use of reinforced brick masonry, a material locally available and economical in its use. Whilst masonry bricks are traditionally brittle and poor in tension and bending, through the use of reinforcing and pre-stressing and thus imposing a state of compression working to the materials strength, Dieste was able to use brick in new forms and to span vast distances.

**GAUSSIAN VAULTS**
The Gaussian vault was developed from Dieste’s appreciation of how an arch is affected by bending. As Torroja (1962: p.167) states ‘bending stresses diminish and finally vanish in the proximity of articulations, yet increase in the intermediate zones.’ Aware of this phenomenon Dieste developed the Gaussian vault, relating the shells form precisely with the bending forces where the risks of buckling are highest. He achieved this form by increasing the depth of the section most at the spans centre through the use of double curvature and diminishing it to become flat as it approaches the articulations or wall. As Dieste states ‘it is to some exemplary individuals that we turn to renew our enthusiasm for inventions that are complex yet, once realized, possess a simplicity and seeming inevitability – for inventions that are not mere novelties’ (Anderson, 2004: p. 183), the Gaussian vault is certainly one of those ingenious discoveries. The Gaussian vault is made up of catenary curves working essentially as a ‘shallow barrel vault that acts entirely in compression’ (Anderson, 2004: p. 75) and thus does not require pre-stressing (Anderson, 2004: p. 144). What makes the vault unique is that the catenary curves are of varying rise, creating in cross-section an s-shaped band as seen in Fig.14. This s-shaped profile exhibits double curvature providing the necessary stiffness to resist buckling and thus allowing great spans with thin shells, his largest 180 feet (Anderson, 2004: p. 75). The form is highly practical both in its relation to the forces it must resist, but also, the repetitive use of the Gaussian form allowed the formwork to be re-used for the entire structure, making its construction economical. Furthermore, the highest catenary curve which rests above the lowest curve provides a welcome opening, allowing natural light to penetrate the interior. The form becoming flat at its junctions also makes the articulations between roof and wall simple. One aspect which no doubt would have displeased Dieste, was the need for steel ties to resist the lateral thrusts which as earlier highlighted can be large in long shallow vaults. As used in Gaudi’s schoolhouse undulating walls could provide a solution to resist the lateral thrusts although the complexity would increase significantly inevitably adding to the construction costs. The wall undulations could align with those of the roof to provide an elegant junction although special consideration would be required in regard to re-using the formwork. Dieste would have undoubtedly considered the many alternatives and whilst more elegant solutions are possible, the Gaussian vault was most successful for its economic credentials, being most widely used in factory applications. The tie is an economical solution although in the eyes of structural artists it is a flaw.
CANDELLA

As a student Felix Candela was often disheartened by the mathematical complexity associated with the forms he so admired (p. 65). The greatest influence on his work, according to Garlock et al. (2009: p. 64) was Robert Maillart who ‘encouraged simplified calculations rather than rigorous analysis.’ This was to become the foundation for Candella’s work. Candella realised that to pursue his interest in form he would need to establish his own construction practice. Candela therefore developed his ideas and intuitive abilities through practice where his prodigious roofing around Mexico gave him some freedom for experimentation. Like Torroja, reinforced concrete was the predominant material used Candella.

UMBRELLA’S

Whilst taking inspiration from a sketch by Amon, Candela was the first to construct the Umbrella form (Garlock et al. 2009: p.98). The umbrella is created by joining four straight-edged hypar surfaces as seen in Fig.15. As small hyperbolic paraboloids the stresses remain similar although the arrangement directs the forces into the groins and the cantilevering effect of the form creates tension at the outer edges as indicated by the arrows in Fig. These forces can be resisted through additional steel reinforcement or the use of small edge beams and Candela often thickened the valleys. (Garlock et al, 2009: p. 99).
Fig. 15 Stresses in Umbrella form. Source: Garlock et. al, 2009: p. 99

Fig. 16

Construction of a tympan

Fig. 17 Rio’s Warehouse, tilted to provide a roof with a sawtooth profile. Source: http://www.revistacodigo.com/

FOLDED HYPARS
Folded hypars are Candela’s adaptation of an Umbrella whereby in the words of Candella two tympans are joined “in such a way that one short edge of each hypar is horizontal to the opposite short edge of the vertical” (Garlock et. al, 2009: p. 122). The result is a form that shifts from a vertical orientation until it becomes horizontal as it cantilevers outward as seen in Fig.17. The twisting orientation alludes to an overall expansion of form creating a dramatic structure which appears to defy gravity, exaggerated from certain perspectives as seen in Fig.18. The folded hypar was not widely used by Candela in comparison to umbrellas, as the formwork and drainage is more difficult (Garlock et. al, 2009:p. 122), restricting its use predominantly for sculptural purposes or dramatic roof features as was used in La Candelaria subway station, Mexico. Despite horizontal planes being inefficient against bending, the momentary horizontality, seen in folded hypars, is made possible as the dead weight and therefore subjecting forces become reduced as the shell extends outwards. The horizontal orientation therefore carries only the forces from its own weight and benefits from the stiffness provided by the forms overall torsion. Horizontal only at the forms edge, it immediately begins to shift vertically in accordance with the increasing bending forces. As seen in Fig. 17, in elevation the folded hypar is in fact a direct representation of a bending moments diagram for a cantilevered beam, the forces by which the folded hypar assumes. The forces are directed to the valleys and the form becomes increasingly deep in section adopting the form of recurrence, efficiently shaping upward. As Garlock (2009: p. 123) states Candela ‘found that the stresses in the main body of the shell were negligible, and that the valley and the reinforcing steel at the support could be sized using the cantilever method.'
Los Manantiales Restaurant at Xochimilco is one of Candela’s most notable buildings and was the first groined vault attempted to intersect four hypars. In a groined vault, forces travel to the groins and are directed to the supports. Candella therefore thickened the groin sections and designed them to curve to provide continuity of the overall curved form.

3.4. The role of Computer-Aided Design and Computer-Aided Manufacturing

As French (1988: p.18) states ‘an engineer always has to balance manufacturing cost against performance, and so the components he designs have shapes which are easy to make, rather than the best for the task.’ This restriction toward complexity is foreign to nature, where form and performance is a matter of survival and where inefficiencies overcome by mass are understood to represent a false economy. As Benyus (1996: p. 254) suggests nature runs on information and mature systems favours quality rather than quantity. In our battle towards sustainability this shift towards more mature systems based on information and quality is
paramount. In the building and design sector this is likely to be well bolstered by the advancements in Computer-aided design (CAD) and the development of Computer-aided Manufacturing (CAM). CAD software allows designers to realise increasingly complex forms and provides engineers with the tools to analyse them. To what would come as delight to Dieste, no longer do architects have the excuse to ignore the work of Gaudi or engineers being pre-supposed to posts and beams favoured due to the simple and reliable calculations. The age of computer-aided manufacture as Michael Stacey observed elevates the designer so they ‘no longer need to be remote from the manufacturing process; the 3-D model can become the building and all its component parts (Kaplinsky, 2006: p.67). CAM technology therefore lays an emphasis on design as the costs of manufacturing become reduced due to the removal of labour and the investment can shift to design, producing information rich, quality designs. Whilst an exciting prospect, CAM technology remains in its infant stages and as Kaplinsky (2006: p.68) highlights, at present, very few buildings are actually manufactured prior to even considering computer-aided manufacturing. In 1996 Benyus (p.116) described with enthusiasm the potential of 3D printers. Today, the clear advantage of this technology suggests that further advancements will be inevitable and the process will become possible on greater scales with the use of more robust materials. A great power of CAD software such as Microstations Generative components is its ability to use repetition and adaptable components which can rapidly speed the process of design and could allow components to be manufactured and later brought together to make the whole. What particularly excited Benyus (1996: p. 116) about CAM technology was the layering process of the manufacturing which could open endless possibilities in the use of composite materials as the technology continues to advance. With the design completed in its totality prior to its manufacturing there is also the potential of reducing wastage as the manufacturing can be better planned.

Despite the enormous possibilities presented by CAD advancements there remains some trepidation among the design and engineering community. As cautioned by Arup’s John Thornton ‘the danger is that computer power triumphs over design and takes away the need to simplify, rationalise and understand the material (Kaplinsky, 2006: p.68).’ Edward Segal also cautions, stating that ‘if used improperly, computers can lead designers to generate irrational forms that can be analysed and made to work but are not structurally efficient.’ Although Segal also accepts that ‘for rational designs, however, computers can serve a purpose’ (Garlock et al, 2009: p.160). As with most technological advances the additional power provides a risk of being abused. The increasing ease of CAD technology makes the realisation of complex and seductive forms increasingly simple and there is a danger that this will over-ride the critical pursuit in which architecture is derived. Despite the potential benefits of digital technologies Dieste warns ‘the reader to exercise critical discrimination – between novelties and profound complex and responsible innovations’ (Anderson, 2004: p.17). The many advantages of CAD technology make its rise inevitable and when used appropriately could be an enormous boost in our battle towards sustainability. But as emphasised in the philosophy of biomimicry, technology must always be overlooked by a degree of wisdom.

3.5. The influence of Material innovations
As earlier highlighted a materials properties plays a critical influence on the structures potential forms and capabilities to resist certain forces. As Galileo had earlier hypothesised, and as summed up by Thompson; to overcome scales of magnitude ‘we either change the relative proportions, which will at length cause it to become clumsy, monstrous and inefficient, or else we must find a new material, harder and stronger than was used before’ (Thompson, 1917: p.19). ‘Once reinforced concrete had been invented,’ as Torroja highlights, ‘it was possible to use its tensile resistance for much lighter structures’ (Torroja, 1969: p. 19) and therefore much greater spans were made possible. According to Mahmet Sarikaya ‘we are on the brink of a material revolution that will be on a par with the Iron Age and the Industrial Revolution,’ this age, as Sarikaya highlights will be one driven by biomimetics (Benyus, 1996: p.95). Tsui believes we are entering an ‘exciting and evolutionary point in our development of materials that approach the supreme efficiency of nature’s structures’ (Tsui,1999 :p.24). Material innovation is important not only to provide new possibilities in structural forms, but is also important in our quest to conserve resources, substitute non-renewable materials and provide building skins with an increased number of functions. In recent decades we have gone through what Benyus has labelled as the silicon age. Engineer and Architect Dr. Werner Sobek has explored the application of load bearing glues and states that his R129 prototype is the thinnest glass shell ever built. According to Sobek the shell thickness of ten millimetres with a span of eight and a half metres provides a relationship one tenth that of an eggshell. Sobek stipulates that the possibilities of such a shell could be spans as large as 20-25m. Despite this impressive feat as well as the many other material innovations, another idea being championed by Sobek is even more radical.

3.6 Alternative schools of thought to improve structural efficiency

The next step in structural efficiency according to Sobek is the idea of adaptive elements within a structure (Woodruff 2008). As ‘stresses follows stiffness’ (Anderson 2008: pp.223) the idea being championed by Sobek is for the a highly loaded member under the most stress to be artificially weakened, distributing the stresses more evenly to the neighbouring members. He suggests that if this is done in a clever way “you might save 50% of materials.” Essentially adaptive elements substitute material with very small amounts of energy to create subtle movements, which Chrisine Lemaitre says can “achieve a big change in the system.” In the quest for greater structural efficiency Sobek suggests architects and engineers should collaborate with aeronautical engineers who have focused their attention on this quest for many decades. Whilst adaptive elements suggest an exciting future for structural design, the complexity involved is likely to render it many decades from becoming feasible in a commercial sense. Much of Sobek’s work today as previously highlighted focuses on light-weight shell design using cutting edge materials.

Another exciting development in material innovation being explored by biomimetics such as Paul Calvert is the idea to learn from nature’s ability to self-assemble. As Benyus highlights;
'whereas we spend a lot of energy building things from the top down-taking bulk materials and carving them into shape-nature does the opposite. It grows its materials from the ground up, not by building but by self-assembling.' (Benyus, 1996: p. 104)

Whilst the idea of growing structure’s sounds like an idea of fiction, like 3D printers, the developments will begin at a small scale and one day it could be used to create much larger components or even buildings. The environmental benefits of such a breakthrough could be substantial. Structure’s that grow could expand forming to suite the forces in which they are subjected. Whilst distant propostions, the idea of learning from structural lessons from orchids could be applied to the built environment today.

1. 1. BIOMIMICRY OF ORCHIDS

4.1. Why Orchids?

Orchids come in a multitude of forms despite the imposed limitations of their material properties, indicative of the power of limits. Orchids are often beautiful and through their forms, elegantly span across space, often seemingly defiant to the effects of gravity. Whilst undoubtedly benefiting from their light profiles, in consideration of the scales of magnitude, the relationship between material strength to span is likely to be similar to structures in the built environment. Whilst orchids remain in fluctuation from growth to death, for a period of time they hold their form more or less in a static equilibrium, indicative of structural integrity. Many of the forms and techniques used by structural artists are evident in the forms of orchids as well as a number of unique forms and techniques not common in the built environment. Whilst orchid forms are not restricted by a need for practicality in construction, which is a critical consideration for structural artists, advancements in CAD and CAM technologies provide new possibilities to creating increasingly complex and organic forms. Orchids therefore represent plausible models in structural form.

For the purpose of this thesis it should be noted that the structural integrity of different orchids appear to vary. Whilst all have evidence of structural integrity, some species provide more useful case studies, whilst others due to the inconsistencies in form and high number of deformations raise doubts regarding their structural merit. Furthermore flowers with less consistent orientations appear to adopt more generalised forms to withstand forces from varying directions, which is an uncommon requirement in contemporary structures, although this is likely to gain greater importance in the future. It was found that the most appropriate case studies were orchids with heavier sections, consistent orientations and forms with elements that cantilever in a horizontal plane requiring an intelligent form to withstand increased bending stresses. The Cymbidium orchid was an ideal example of such a species.

1. 1. METHODOLOGY
The forms of orchid vary considerably between different species and therefore a range of flowers have been selected for study to provide an adequate sample for the purpose of this thesis.

It was deemed most accurate to analyse the orchids with the assistance of a 3D scanner. The scanner would transform the living orchids into digital 3D models and thus transform something dynamic to something more tangible to be measured. The 3D scanner, as seen in Fig. 20, operates through the use of a laser. The laser collects data as its path is obstructed by the object. As it collects data it converts this into a digitalized model. The laser is fixed, so to achieve scans of 3-Dimensional objects the circular base, by which the object rests, rotates, rises and falls to allow the whole object to be exposed to the axis of the laser beam.
Whilst the potential for such technology is exciting, it was found that the complexity of the orchid forms, at present precedes the capabilities of the machine in question and the ambitions of the author. A major limitation of the technology is its inability to scan concave surfaces, which are common in the forms of orchids. It is also beyond the capabilities of the fixed laser beam to recognise surfaces that are blocked in both directions by other surfaces in relation to the laser beams axis. In the three-dimensional double-curvature of orchid forms, this was a common occurrence. To attempt to overcome this, the orchids were fixed to a stand and positioned upright to expose the greatest amount of their surface perpendicular to the laser beam. Outcomes were improved, although the stand itself often interfered with the scanning.
Furthermore, being held by the stand, the orchids were less secured and movements during the scanning process interfered with the accuracy of data collection. The laser was also lost in darker surfaces where the beam is absorbed and thus no data is registered. This experience highlights the role in which technology has to play, although it provides caution, as while the potential for such technology is evident, whilst in its infant stages, technologies can remain temperamental. The erratic scans demand a revision of the research scope, whereby greater emphasis will need to come from general observations and analysis from photographs.

4.3. ANALYSIS AND FINDINGS
Despite the great variety of forms, common structural techniques were found amongst the different orchid species. The first technique which is seen regularly is the use of double curvature, adopting similar forms to that of the hyperbolic paraboloid, with the use of an intersecting arch and cable. This sound structural arrangement forms the basis by which diversity springs, with species adjusting the degrees of curvatures and size of petals. This can be seen in Fig. 22. The Arachnis hookeriana for example, due to its sporadic orientation, adopts a fierce inward curvature, establishing cylindrical like sections. With a section consistent in all directions, cylinders provide an efficient form for beams subject to bending from varied orientations. It is also common for the double curvature of orchids to exhibit a degree of torsion, or triple curvature, to realign the efficient double curvature form against the forces of gravity, thereby maintaining equilibrium.
This technique is seen again in the Labellum of many orchids, such as the Cymbidium, as can be seen in Fig. 23. Whilst adopting the double curvature with great effect, the Cymbidium labellum introduces a form not seen in the built environment. The curvature in section has an element of rectilinearity not seen than the conventional hyperbolic paraboloid, as can be observed in the Fig. 24 illustration. The cable is quite pronounced in its verticality providing the labellum with a deep overall section allowing it to resist bending and cantilever outward. The cable in fact, turns inward at its height. This technique provides additional stiffness to the form, acting in a similar manner to perhaps that of an edge beam. The cables more rectilinear form
whilst less efficient is in fact quite deliberate and ingenious, as will be explained. Another aspect not seen in the hyperbolic paraboloids of the built environment is the use of internal ribs as seen in Fig 24. These internal beams act as reinforcement to the relatively flat base, which would otherwise be inefficient to resist bending. When force is applied downward to the lip of the labellum the stiff reinforced base remains structurally stable whilst the weaker surrounds distribute the stresses up the cable walls. The rather square transition from arch to cable is a weakness in the labellum form and this weakness acts as a hinge, whereby the inward curving cable, already naturally inclined by its curvature bends further inward to absorb the stresses. As can be seen in Fig. 25 the labellum form uses hinges both at its articulation and later as the form breaks from its horizontal projection to hang vertically, eliminating bending stresses by balancing the remainder of the mass in equilibrium rather than cantilevering. The hinge at the labellum’s articulation works in unison with the cables inclination to curve inward, for when forces are applied to the lip, the hinge initially provides some flexibility reducing undue stresses on the overall form. The hinge flexed to its relative capacity, forces begin to accumulate and the cable wall is stressed turning further inward. The cables ‘edge beams’ catch on the column, which as seen in Fig. 24 has a form shaped for this very purpose. The column aligned directly from the stem is robust in its materiality and strength and therefore supports the labellum against momentary live loads, which otherwise could destroy the labellum and jeopardise the species reproduction. As can also be seen in the elevation in Fig. 25 the arch curvature is broken by a momentary hump, which is an inverse dome. The dome commences at the completion of the internal beam, where the arch in its totality ends and where the reversed curvature of the dome extends the form further outward. When force is applied to the underside of the inversed dome, the effect is for the orchid form to open outwards. As this force is not one that the dome would naturally experience, its influence to the overall form is indicative of the movement through its manipulation. The inversed dome maintains the forms overall compactness, inward emphasis and overall stability. The use of dome like forms is the second prevalent technique used by orchids.
As was the case with the previous technique, orchid forms quite often adopt dome forms although these vary in curvature and size, again establishing a great diversity in forms as seen in the examples in Fig. 26. More pronounced domes appear to provide more stable forms as seen in the Cymbidium Dorsal Sepal as seen at the top of Fig. 26. In the case of the cymbidium, not only is the dome used to provide a depth in section, but the form also adopts upturning edges which contrast directly to profundity of the dome providing bending resistance along the forms entirety. Upturned edges was a technique also used by Heinz Isler in his Heimberg Tennis Centre as seen in Fig. 28. In Isler’s tennis centre the upturned edges establish double-curvature,
which provided his thin shell with the necessary resistance against buckling (Anderson, 2004: p. 102). Likewise the Cymbidiums Dorsal Sepal uses the technique of upturned edges to provide the structure with stiffness. As the form acts as a cantilever, the bending will be greatest near its articulation. As seen in Fig. 27, this is where the upturning of the edges are at their greatest height. The inward turning edges appear to adopt a similar torsion to that of Folded Hypars, whereby it rotates to become horizontal around the dome to resist outward thrusts before returning to its vertical orientation. The ‘edge beams’ appear to play a critical role in the structural stability of the form, acting in tension in the longitudinal direction whilst providing resistance to buckling in the perpendicular plane. Assisting the resistance to bending, near the articulation, is the use of recurrence as seen in Fig. 27 and the recurrence also features in cross-section becoming thickest at its symmetry of axis, helping to reduce the risks of buckling. The symmetry of axis where the thickness in the longitudinal section is greatest also adopts a relatively straight profile where the forces are directed into the stem. As the form continues to extend outward it begins to exhibits a curvature before turning into the dome form. From general observations the author suggests that the use of dome forms are more prevalent in the more compact orchid forms which have wider petals, whereas the hypars are the preferred forms when greater emphasis is on longitudinal spans. As seen in the elevation in Fig. 27 the overall form from its articulation outward, in consideration to its cross-section, begins as a cable, moving into an arch where at its tip the upward turning edges again produce a cable. The sinuous curves produced from these transitions and likely to gain their stability and form from the upturning edges which acting in tension support the outward projection. The lateral thrusts from the dome form is also likely to be absorbed by the upward edges acting in tension perhaps in a similar manner to steel ties, used in the past around domes.

Fig. 26 The use of dome like forms in orchids
Another factor of orchid’s forms is of course the flexibility of their materiality. Like the use of hinges the flexible materiality of orchids tends to be used to reduce the accumulation of stresses. This can be beneficial to resist momentary stresses although it can too often result in more permanent deformations.

**CONCLUSION**

In conclusion, we are at a critical moment in history, whereby sustainability is rapidly becoming
a matter of human survival. Biomimicry appears as a highly plausible guideline whereby inspiration from nature could provide humanity with the framework for more intelligent design. The built environment, a major influence on sustainability, must play a critical role and developments in structural efficiency provide enormous scope for significant improvements. Biomimicry has long inspired architects and engineers and with CAD and CAM technologies advancing steadily, the next generation of organic, structurally efficient forms devised from the forces the building is subjected is upon us. Structural artists as well as the diverse orchid forms are terrific examples of the ‘power to tap limits.’ Orchid forms provide many significant lessons in structural efficiency and as building requirements continue to change many of the unique techniques could become increasingly appropriate for the built environment.

SUGGESTED FURTHER RESEARCH

Orchid forms represent a wealth of knowledge for the structural design community. Orchid forms tend to have less precision than those of the built environment, therefore the scope for lessons to be taken, refined and applied are considerable. It would be worthwhile for the study of orchid forms to continue. As orchids are seasonal a longer period of study would be useful. Analysis of the forms structure through complex engineering software would be the logical next step. Lastly, the study of nature’s forms for lesson in structural efficiency should continue to broaden its scope, well beyond that of orchid forms.

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