# Bio-inspired Bridge Design

**Article** · August 2015

DOI: 10.1007/978-3-319-09287-4_10



**2 authors:**

Nan Hu
The Ohio State University



Peng Feng
Tsinghua University

# Chapter 10
# Bio-inspired Bridge Design

**Nan Hu and Peng Feng**

**Abstract** This chapter reviews the development of the bio-inspired concept on bridge design in the past two decades from two major forms: stationary forms and movable forms. The objective is to show how the inspiration from the biological world has influenced recent bridge designs and discusses how the bio-inspired idea could transform into a new language for the future bridge design industry. Four major challenges of the marriage between biology and engineering were discussed and latest endeavor on each aspect are presented. Thus, a close multidisciplinary collaboration may help engineers build more sustainable and smart structural systems for bridges in the twenty-first century.

## 10.1 The Inspiration from Nature

A paradigm on biomimetics has emerged in the past two decades featuring the translation of biological inspiration into a powerful problem-solving tool (Bar-Cohen 2011, 2012; Bhushan 2009; Bonser 2006; Petra 2008; Vincent 2006; Vincent and Mann 2002; Yoseph 2006). Bio-inspired design is perhaps the oldest methodology throughout the thousands of years on man-made construction history. In ancient times, the designs of early architecture were more or less inspired from the natural forms even without being aware of such influence. Later in history, pioneer architects led by Antoni Gaudi and Frank Wright started to actively consider nature as design prototypes and incorporated that philosophy into much of their uniquely creative designs. The major drawback of biological inspiration in

N. Hu (✉)
Department of Civil and Environmental Engineering, Michigan State University,
East Lansing, USA
e-mail: aaronx26@gmail.com

P. Feng
Department of Civil Engineering, Tsinghua University, Beijing, China
e-mail: fengpeng@tsinghua.edu.cn

 
F. Pacheco Torgal et al. (eds.), *Biotechnologies and Biomimetics for Civil Engineering*,
DOI 10.1007/978-3-319-09287-4_10

architectural design is that only the geometrical aspect of biological creatures that commonly aimed to achieve visual expression were learned without much attention to efficiency and economy. Review articles about the development of bio-inspired architecture can be found in papers (Aldersey-Williams 2004; John et al. 2005; Knippers and Speck 2012; Petra 2008).

Architectural design and structural design are professions that have a historical misunderstanding, even though the core of both professions is shaping man-made structures. That was not the case during most of history because up until the end of the eighteenth century, the two professions were as one. After the Industrial Revolution, engineering developed as a discipline in its own right with a scientific basis and moved increasingly further away from architecture. The rationale behind the history of structural design did not change much no matter the scale of a structure, which featured a search on a cost-effective and performance-efficient design without losing its elegance. A structural design can be regarded as a work of art by the following three tenets: economy, efficiency, and elegance Billington (1983) Bridge design, in particular, is a unique regime where engineers evolved a dominant role over architects and are capable of designing a work of art in their discipline.

Biological inspiration on bridge design is not a recent topic. Ancestors started to build ancient bridges after recognizing how the natural world used structural forms to span physical obstacles. In fact, all basic types of modern bridge forms (beam, arch, and suspension) can find their ancient prototypes in nature (Tang 2007). The only difference is that ancient people built the bridges with natural materials (wood, vines, stone, and ropes) while modern technology uses steel, concrete, etc. Even new structural forms show connections with natural forms. For example, the Hacking Ferry Bridge's three-way deck (45 m on each side) in Fig. 10.1b not only provides sufficient structural stability but also necessary clearance for the channel. The Webb Bridge (Fig. 10.1d) at Melbourne has a curve layout instead of a straight one, but provides an interesting experience to the bicyclists and pedestrians. Architects or engineers may not directly learn from natural forms, but it does show that biological creatures can be regarded as a significant resource with a variety of interesting designs.

Limited papers are found on the discussion of bio-inspired bridges. Hu et al. (2013) summarizes five main aspects in nature (Table 10.1) that may inspire the development of future bridge systems: geometry, structure, kinetic mechanism, energy efficiency, and intelligence

It is shown that biological inspiration is a very promising route to inspire bridge design not only in traditional stationary forms but also in emerging movable form. Thus, the objective of this chapter is to present a review on recent bridge projects to show how the bio-inspired philosophy has impacted conceptual design in the past and will bring a new language in the future that potentially could encourage a marriage between biological knowledge and bridge design.


**Fig. 10.1** The biological shape and structural shape in bridge **a** shape of starfish (*photo* Wikimedia Commons); **b** Hacking Ferry Bridge (*photo* Wilkinson Eyre Architects); **c** earthworm shape (*photo* Wikimedia Commons); **d** Webb bridge (*photo* bridgeworld.net)

**Table 10.1** Toward the bio-inspired bridge

| Prototype in nature | Bio-inspired design goals |
|---|---|
| Geometry | Eye-catching and signature bridge |
| Structures | Material-adapted supporting and deck system |
| Mechanism | Deployable and moving bridge |
| Energy | Sustainable and multifunctional bridge |
| Intelligence | Self-control and smart bridge |

## 10.2 Bio-inspired Form-Finding

Biological inspiration on engineering design has developed in various aspects, but still faces new challenges. For example, the tree is a classic prototype in bio-inspired research (Mattheck 1998). The trunk and supporting branches of a tree is a brilliant example of structural optimization. From a morphological perspective, many trees are subjected to wind load and evolutionary transform into an

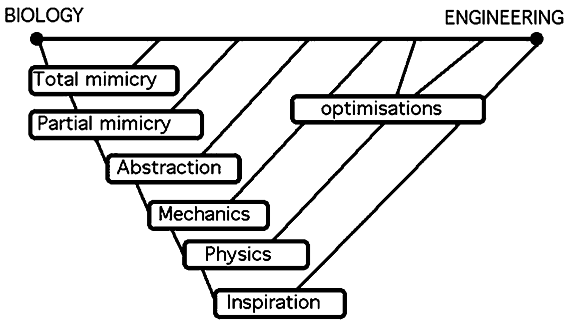


**Fig. 10.2** Biomimetics "map" (Vincent 2001)

adaptable structural form. From a sustainability perspective, engineers were also trying to rediscover intelligent features of trees, such as the ability to self-adapt, be self-controlled, and be energy efficient, which leads to some interesting sustainable designs. Vincent (2001) developed a biomimetic "map" to clarify the transfer from biology to engineering, as shown in Fig. 10.2.

The more one can move further down from the natural origin (top left), the more powerful the concept will be. It illustrates that inspiration from biology at the top level can be more adaptable within the engineering discipline, even though the final product may vary far away from the prototype founded in nature. There are many versions of this diagram which could be drawn for any engineering design problems.

For structural design, some engineers may claim with buildings and bridges as large-scale man-made structures, it is difficult to reach the efficiency as biological creatures. However, many engineers have been sparked by the bio-inspired philosophy and are dedicated to the development of bridges in future generations. After simply borrowing geometrical feature from nature for centuries, recent efforts in bridge design and construction by both architects and engineers have shown inspiration from the mechanistic and the material level. Table 10.2 shows many recently built bridge projects with a varied level of inspiration from different aspects in the nature. Most designs are still within the low level of inspiration (total mimicry, partial mimicry, and abstraction), sometimes resulting in many awkward shapes rather than efficient structural forms. Fewer designs featured a high-level of inspiration, in which design problems are addressed by biomimetics. A logical explanation is that those engineers are aware of bio-inspired idea, but they are not capable of finding tangible resources that could revolutionize their designs.

### *10.2.1 Stationary Forms*

Traditionally, bridge design is still a classical static problem searching for efficient forms across existing roads and rivers. The best bridge design in history has been regarded as structural art, because it shows very good balance on economy, efficiency, and elegance (Billington 1983).

**Table 10.2** Recent bridge projects with varied level of bio-inspiration (Hu et al. 2013)

| Bridge name | Built | Location | Main bio-inspired aspect | Inspiration level |
|---|---|---|---|---|
| Campo Volantin bridge | 1997 | Bilbao, Spain | Structure of beam | Mechanics |
| Foldable bridge | 1997 | Kiel, Germany | Kinematics of beam | Mechanics |
| Butterfly bridge | 1998 | Bedford, UK | Structure of arch | Partial mimicry |
| Nesenbach valley bridge | 1999 | Vaihingen, Germany | Structure of beam and pier | Mechanics |
| Millennium bridge | 2001 | Gateshead, UK | Kinematics of main arch | Abstraction |
| Ribble Way bridge | 2002 | Lancashire, UK | Shape of layout | Abstraction |
| Webb bridge | 2003 | Melbourne, Australia | Shape of layout | Abstraction |
| Rolling bridge | 2004 | London, UK | Kinematics of beam | Mechanics |
| Dragon bridge | 2008 | Recklinghausen, Germany | Shape of superstructure | Total mimicry |
| Chords bridge | 2008 | Jerusalem, Israel | Cable-stayed structure | Abstraction |
| Henderson bridge | 2008 | Singapore | Shape of beam | Mechanics |
| Double Helix bridge | 2009 | Singapore | Structure of beam | Partial mimicry |
| Chunhua footbridge | 2011 | Shenzhen, China | Shape of layout | Total mimicry |
| Peace bridge | 2012 | Calgary, Canada | Structure of beam | Abstraction |
| Dragon Eco bridge | 2012 | Chongqing, China | Structure of arch | Partial mimicry |

Not coincidentally, structural forms in nature also integrate these three tenets, ranging from a plant stem to animal skeletons. The awareness of learning from natural shapes pushed architects and engineers to think out of the box in many recent bridge designs, practically in the design of small-scale structure such as pedestrian bridge. Some architects have realized the benefit of using bio-inspired philosophy to improve visual impact and esthetic value of a pedestrian bridges, but this leads to the tendency of defining the structural forms by architects which leads to extravagance in pedestrian bridge design (Gauvreau 2002). Two examples in Singapore are shown in Fig. 10.3a, b. The curvilinear steel “ribs” along the side of the Henderson Road Bridge may be inspired from natural waves, while the double helix bridge was inspired from the shape of the DNA. Both have become a new landmark for the community. However, a partial mimicry of the geometric shape from nature led to awkward designs with difficult construction and high cost. The efficiency and economy of these designs are questionable. The Chunhua footbridge (Fig. 10.3c) at Shenzhen, China, copied the shape of a flower, but it is not a cost-effective design compared to a regular design. Another recent controversial design

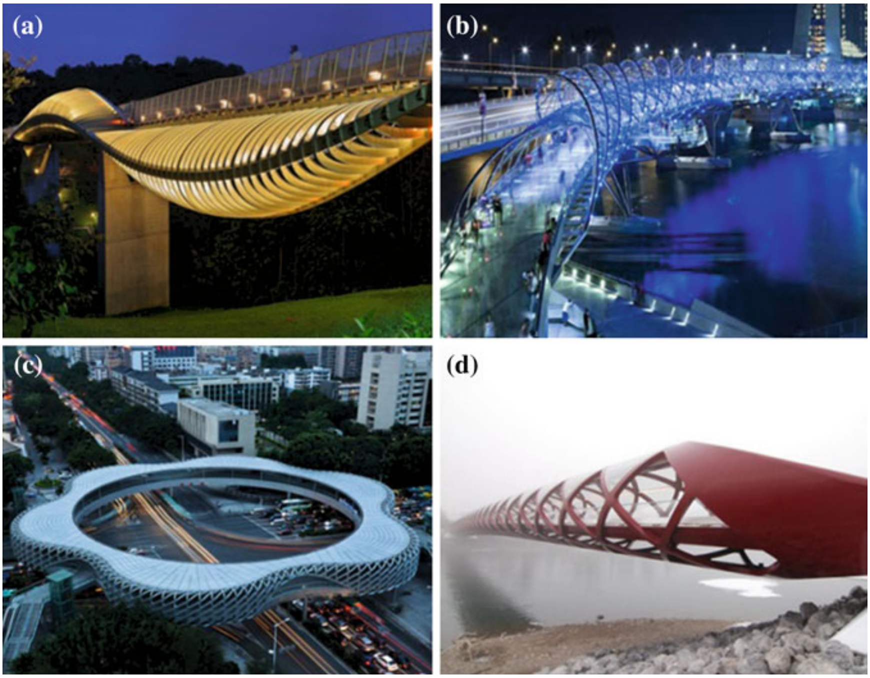


**Fig. 10.3** Bio-inspired shape in recent bridges: **a** Henderson bridge (*photo* RSP Architects); **b** double helix bridge (*photo* Cox Architects; **c** Chunhua footbridge (*photo* China Foto Press); **d** Peace bridge (*photo* Nelson Hein)

in Calgary is the Peace Bridge by Santiago Calatrava (Fig. 10.3d), which was inspired by fishbone structures.

The public criticized that this design was too modern in the old downtown. Given that most engineers are not capable of finding inspiration, bionic research should try to establish a database with potential engineering solutions, such as an illustrated guide to flowering plant morphology for learning plant forms.

The efficient natural forms feature optimal material distribution along with elegant shapes. Historical studies on many bridge structures showed that there are two necessary conditions that contributed to the birth of a masterpiece design, i.e., the understanding of structural principles and the efficient use of construction materials. In the past 2 decades, some leading engineers have become increasingly aware of learning from nature so that a variety of bridges were built with inspirations on the mechanical principles of nature. For example, the twin inclined steel arches as the supporting system of the Butterfly Bridge (Fig. 10.4a) were inspired from butterfly wings. The use of arch hangers is similar to the veins in a butterfly wing. In contrast, the Dragon Bridge (Fig. 10.4b) is totally mimicry of a dragon-like skeleton form in which the actual structural system is the girder and column underneath the deck. Santiago Calatrava is a well-known architect with a strong bio-inspired motivation in his designs. Like his predecessor Spanish fellow

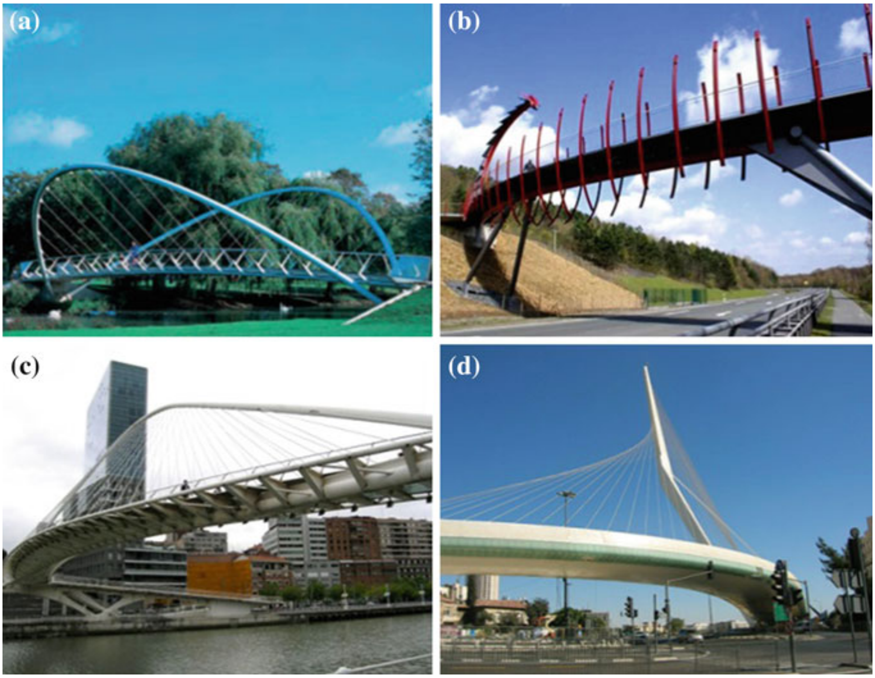


**Fig. 10.4** Bridge design cases of bio-inspired structural system: **a** Butterfly bridge (*photo* Wilkinson Eyre architects); **b** Dragon bridge (*photo* Structure Website, Id 108893); **c** Campo Volantin footbridge (*photo* Structure Website, Id 141499); **d** Jerusalem Chords bridge (*photo* Wikimedia Commons)

architect Antonio Gaudi, many bridge designs by Calatrava were inspired from the structural forms of plants and animals. The main girder of the Campo Volantin Bridge was inspired from the spine structure as shown in Fig. 10.4c, while the tower of the Chords Bridge (Fig. 10.4d) was created with inspiration from the leg. Knippers and Speck (2012) used design principles in natural structure characterized by heterogeneity (geometric differentiation of their elements), anisotropy (fiber-reinforced composite materials), hierarchy (multilevel structure with independent functional properties), and multifunctionality.

It is worth mentioning that both structure and material in nature often appear in a composite way. Thus, the principle of more efficiency and less material in nature also indicates the trend of composite materials and structures for future bridge design.

The innovation of structural forms was reliant on the development of new materials. History clearly demonstrates that new materials are only successful when the substitution phase has been surmounted and when a transition to new material-tailored structural concepts and construction processes occurs (Dooley 2004). Great builders were then liberated from tradition and tried new materials in the old forms: cast iron in a wood arch, steel in a wood truss, and reinforced

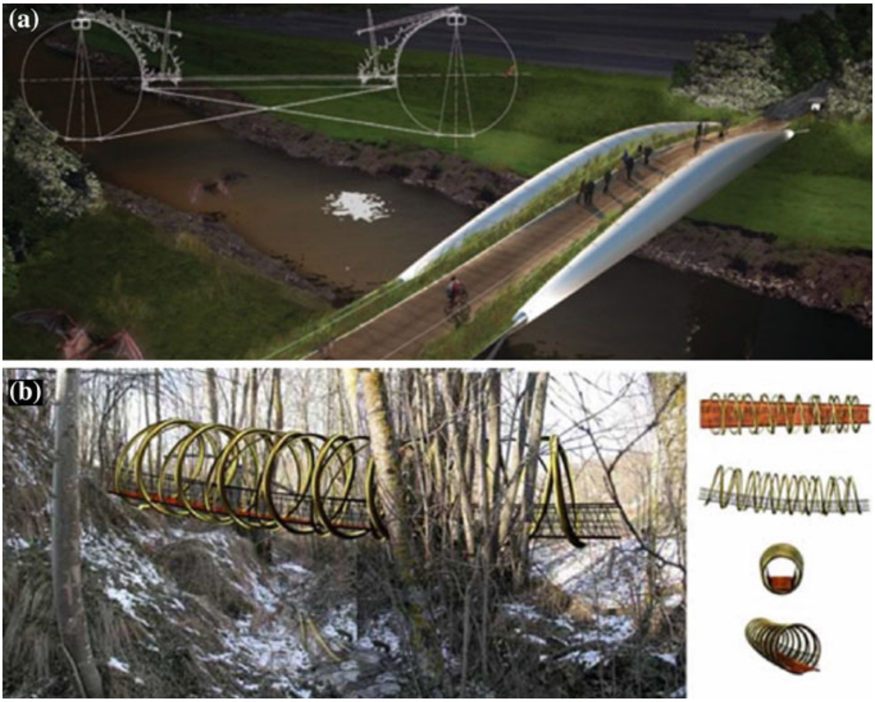


**Fig. 10.5** Bio-inspired design proposals: **a** Douglas river bridge (*photo* Exploration Architecture); **b** Spiral bridge

concrete in a stone arch (Billington 2003). Therefore, future structural form must be material-adapted to achieve high efficiency.

Figure 10.5 shows three bio-inspired proposals of new structural systems. A bridge crossing the River Douglas in Lancashire (Fig. 10.5a) was turning biomimetic research into pioneering lightweight structures with small steel elements and a pressurized air beam.

This design was inspired from the internal pressures seen in nature which create self-supporting structures. Another interesting design (Fig. 10.5b) has a series of intersecting spirals as the structural system. The designers incorporated a seedpod spiral shape from the tree Tipuanatipu and a rectilinear lattice seen in the Euplectella as bridge cover (Dollens 2005). The spirals also reflect the colors of the trees, light so that they will merge into the environment. It is noted that the optimized structural form in future bridge designs should utilize appropriate material-adapted form and certain manufacturing technology.

Energy costs on man-made structures are always a big concern. Future bridges may also play an important role relating to sustainability and the use of green energy. “Green” bridges are designed to reduce the overall impact of the built environment on the natural environment. The idea of “running on natural energy”

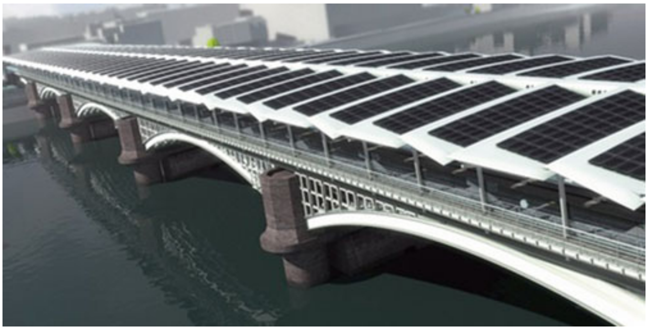

**Fig. 10.6** The solar panel on Blackfriars bridge (Hu et al. 2013)

should not only be embodied in the period of construction, but also be extended to the whole life cycle. Photovoltaic solar panels for example could be installed on the bridge so that it could provide sustainable electricity for any use. The renovation project of the Blackfriars Bridge over the Thames River led this old bridge to a very notable landmark as shown in Fig. 10.6.

The power produced by the photovoltaic panels on the roof can support Blackfriars station's overall power requirement. The critical issue for developing future bridges is how to make best use of natural energy. Future proposals have taken the sustainable issue into account. Wilkinson Eyre Architects proposed a botanic bridge in 2002 at the gateway to the University of Newcastle, which provides an ecological space above the bridge, as shown in Fig. 10.7a. Bridge structures are built to minimize material use and recycled natural resources. Figure 10.7b shows an interesting proposal about the installation of wind turbines between the bridge piers for some heavy wind locations. It is noted that future bridges may also have multifunctional features on energy issues, not only for energy use but also for energy harvesting, energy absorption, and energy storage. The design of such smart structures will require a higher level inspiration that designs the structure in a more comprehensive way.

### *10.2.2 Moveable Forms*

Compared to most stationary forms, another interesting bridge design problem, moveable form, can also be inspired from the kinetic mechanisms in nature. Movable bridges represent an economical way for traffic to cross an active waterway granting passage with little vertical clearance. Wallner and Pircher (2007) summarized three prevailing structural systems of moveable bridges such as bascule, swing, and lift bridges. Those examples of movable bridge in all types, in fact, represent not only a unique mechanism, but also a self-adapting way to the

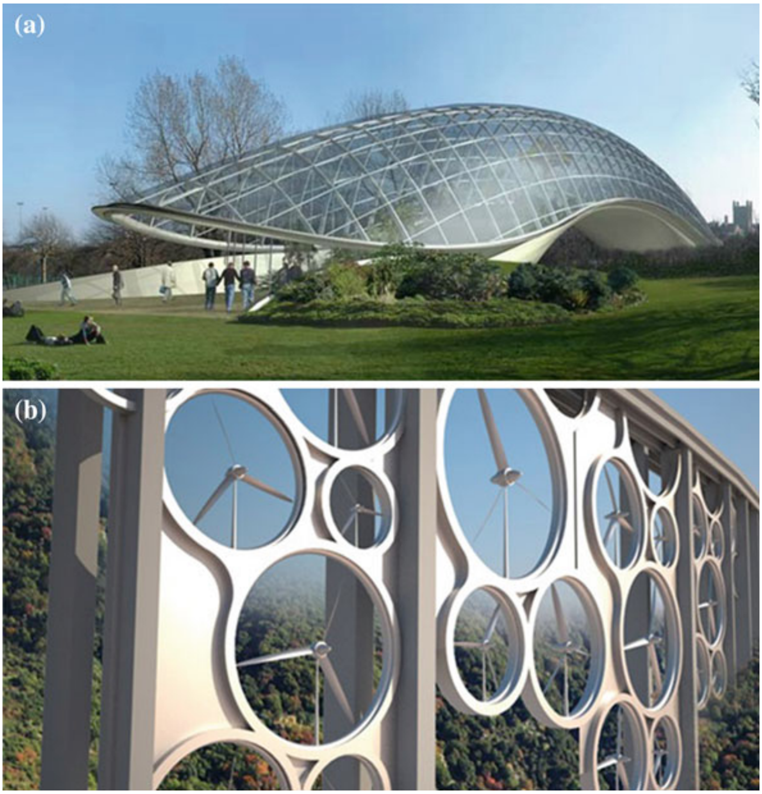

**Fig. 10.7** Environmental-friendly bridge proposals: **a** Newcastle Botanic bridge (*photo* Wilkinson Eyre Architects); **b** "Windy" design (*photo* Francesco Colarossi Architecture)

natural world. Figure 10.8 exhibits Paddington Rolling Bridge with a span of 12.9 m, which has served both pedestrians and the channel in an interesting way.

Although designers may not have completely agreed with the statement that structural form is like a rolling insect, its shape and structural principle coincides with the biological creature. If engineers can try to invite kinematic principles from nature during the conceptual design phase, mechanisms for guiding movements in movable bridges may be better defined. One example (Fig. 10.9) is the Gateshead Millennium Bridge in Newcastle, UK. The designers adopted an unconventional open mode to adapt to channel traffic in the Tyne River. Another example in Fig. 10.10 is the Keil-Horn Folding Bridge with a remarkable trailing design case where three segments are held by cables when it opens for channel traffic.

Some interesting topics on the development of movable bridges includes the use of deployable form (Alegria Mira et al. 2014; Friedman and Ibrahimbegovic 2013; Russell and Thrall 2013; Thrall et al. 2012) and tensegrity form (Korkmaz et al. 2012; Rhode-Barbarigos et al. 2010).

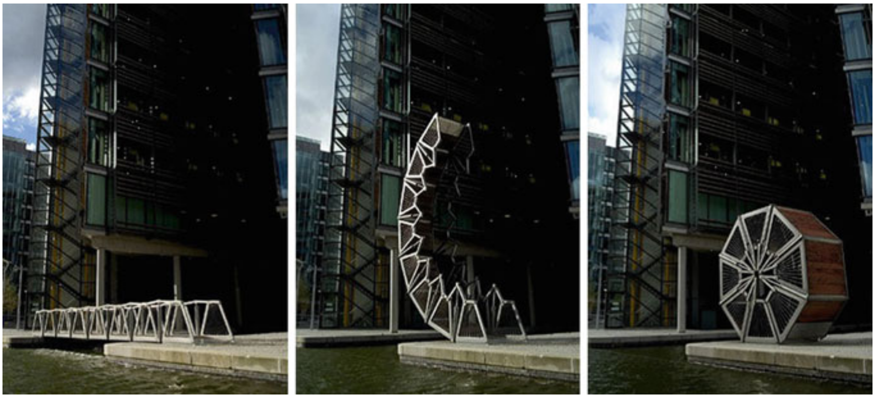

**Fig. 10.8** Paddington Rolling bridge (Hu et al. 2013)

**Fig. 10.9** Gateshead Millennium bridge (Hu et al. 2013)

**Fig. 10.10** Folding bridge at Kiel (*photo* Schlaich Bergermann and Partner)

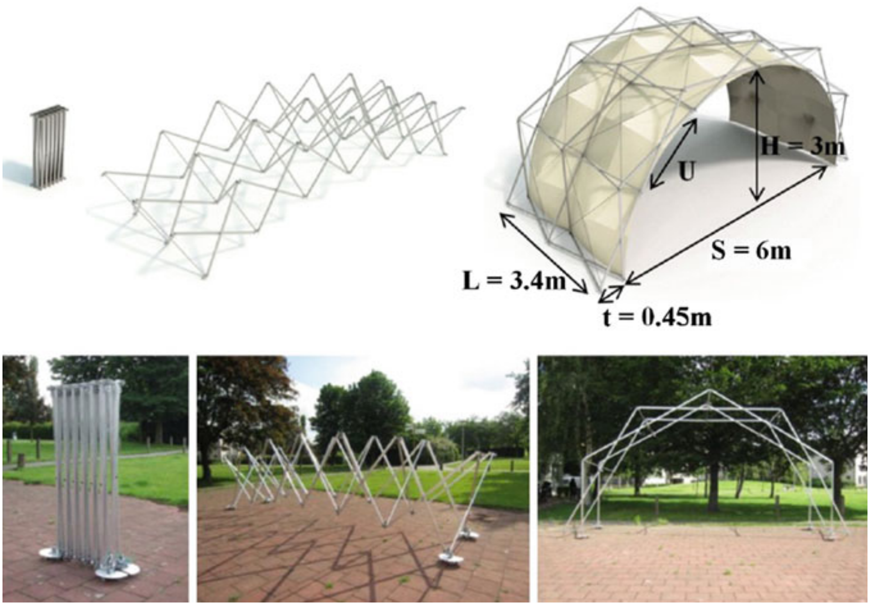


**Fig. 10.11** The concept of deployable scissor arch prototype (Alegria Mira et al. 2014)

Today, deployable structure played a variety of roles in both military and relief operations from emergency to reconstruction. Prototype lightweight forms are studied such as deployable bridge (Ario et al. 2013) and deployable shelter (Alegria Mira et al. 2014), see Fig. 10.11.

Tensegrity structure is spatial structures composed of tensile and compression components in a self-equilibrated state of prestressing. Such concept recently has already been used in bridge design, see Fig. 10.12.

According to Vincent's biomimetic map, these cases discussed above represent the mechanical level of inspiration. In particular, those footbridges provide a more adaptable way than regular footbridge to span a river through combining technologies of machinery and automation.

The development of intelligent and smart bridges is another encouraging goal for the design of active bridges in the near future. The transfer from a "passive" to an "active" bridge through learning from the biological world is a great breakthrough for future smart and intelligent structures. Primary driving factors of the information technology age (such as nanotechnology, microelectronics, and biotechnology) will support the development of intelligent bridge systems and materials (Chong 2004).

The Innenhafen Bridge in Fig. 10.13 shows a remarkable design case where the traditional suspension form is embedded with an intelligent system. It is an adaptive form subjected to different environmental and traffic service conditions. Schlaich (2004) defined the level of intelligence in a structural system by

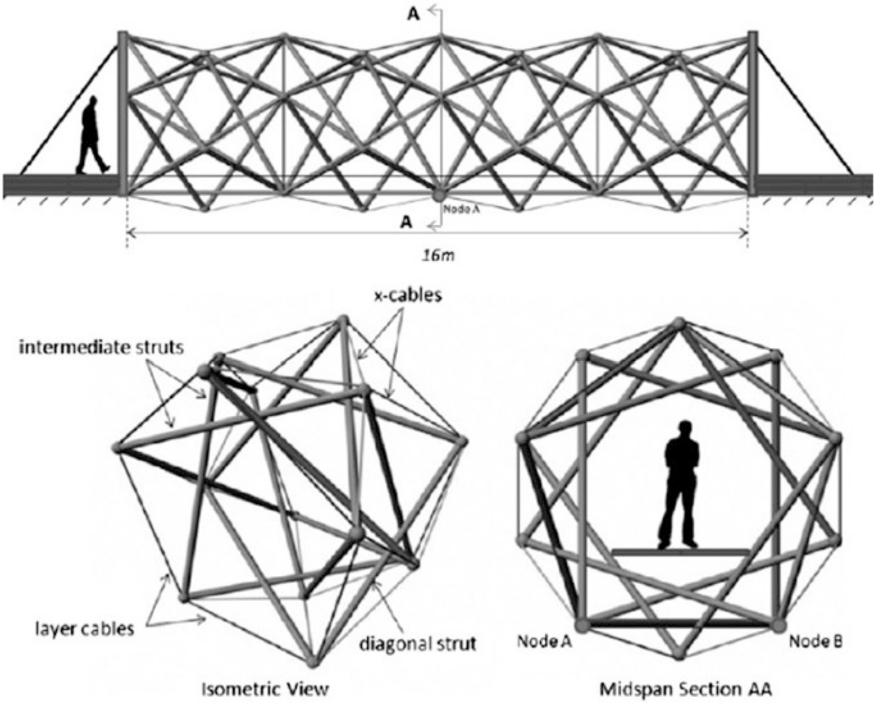


**Fig. 10.12** The concept of tensegrity bridge (Korkmaz et al. 2012)

**Fig. 10.13** Innenhafen Bridge (Hu 2010)

comparing the degree of those electronic devices. A proposal is shown using computer-controlled jacks to actively control the function of stay-cables (Fig. 10.14). This initially solved the problem of uneven deflection when trains ran through the railway bridge. Future intelligent bridges could soon have the capacity of self-control, self-adjust, and even self-repair. Recent endeavors on smart infrastructure can be found (Hoult et al. 2009; Michaël and Dominique 2013; Spencer and Cho 2011; Stajano et al. 2010).

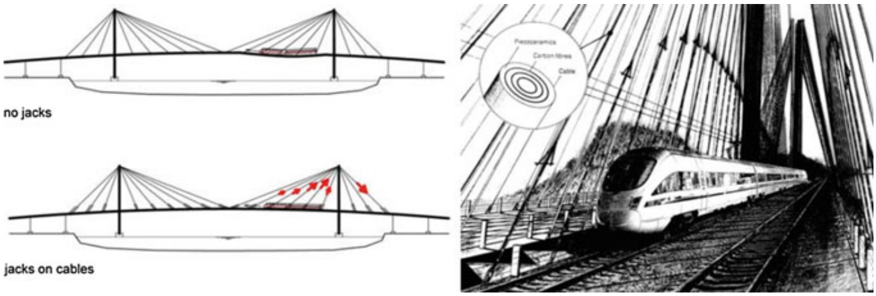


**Fig. 10.14** Self-adjusted cable-stayed bridge (Hu 2010)

## 10.3 Future Directions

A brief project review in the previous section illustrated that bio-inspired philosophy is a promising route for the design industry. Instead of mimicry, both architects and engineers have adopted the mechanistic and material level inspiration and utilized those ideas in the design and construction of man-made structures during the past decade. The latest published book on biologically inspired design by Goel et al. (2014) pointed out four major challenges of the marriage between biology and engineering: (1) solve real problems and document successful applications; (2) develop bio-inspired design theory; (3) develop computational methods and tools; (4) educate new generation students.

For a cross-disciplinary environment in the near future, the bio-inspired design requires the cooperation between engineers and biologists. Future engineering students should not be trapped in professional boundaries and must expand their interdisciplinary knowledge. Figure 10.15 describes a typical process for bio-inspired design, which refers to a regular scientific research procedure that includes experimental investigation, numerical analysis and testing, etc. The most important step in this process is the selection of the appropriate biological prototype. Bionic researchers need to provide resources of prototypes that allow engineers to reference for design inspiration. For example, Biomimicry 3.8, a nonprofit corporation dedicated to biomimicry education launched the world's first digital library of nature's solutions "AskNature." To develop a feasible study on a prototype, it is necessary to work with biologists so that more interdisciplinary knowledge can be transferred. For the past fifty years, many bio-based technologies have been illustrated, such as tough composites based on fiber orientations in wood, tough ceramics based on mother-of-pearl, deployable structures based on flowers and leaves, underwater glues based on mussel adhesive, drag reduction based on dermal riblet on shark skin, flight mechanisms based on insect flight, etc. Recent efforts on bio-inspired design on multiscale smart structures can be found in Barbarino et al. (2011), Espinosa et al. (2009), Giurgiutiu (2007), Hurlebaus and Gaul (2006), Kovač (2013), Liu and Jiang (2011), Mudupu et al. (2008),

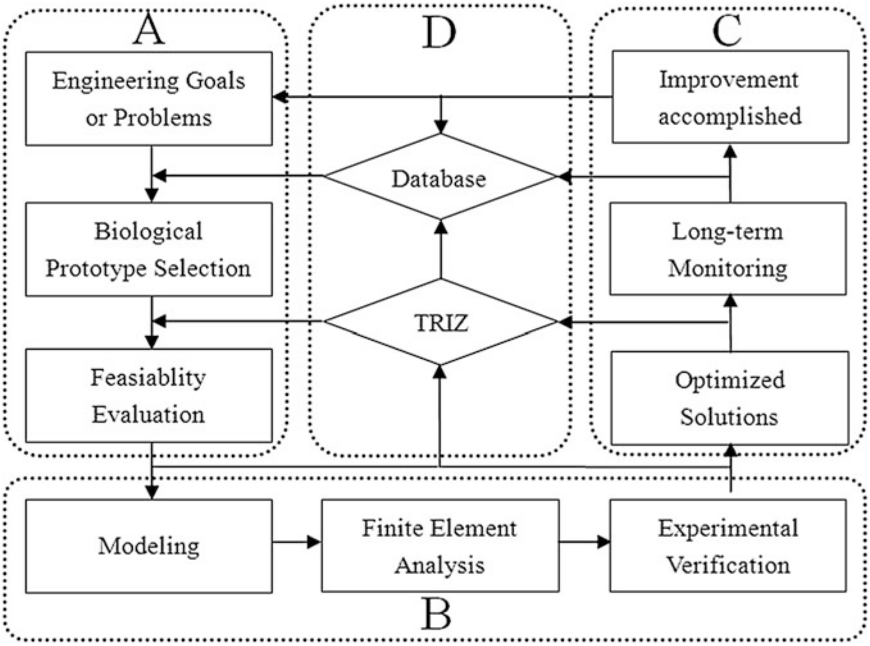


**Fig. 10.15** The procedure of the bio-inspired strategy (Hu et al. 2013)

Singh et al. (2012), Stephen and Christopher (2012), Thomas et al. (2012), Yeesock et al. (2010).

Beyond the success of learning a particular biological structure or mechanism, the search for biological analogies in the conceptual design process also requires design theory to aid in systematically generating new and novel ideas. The Theory of Inventive Problems Solving (TRIZ) has become a significant method that effectively analogized the interaction between engineering and biology. Any technical contradictions can be quantified by transforming the application into a measurable and mathematical algorithm. The latest works for helping engineers to connect and identify biological phenomena can be found in Mak and Shu (2008), Nagel and Stone (2011), Nagel et al. (2010), Sartori et al. (2010), Shu et al. (2011), Srinivasan et al. (2011), Tomiyama et al. (2009), Trotta (2011), Wilson et al. (2010), Xing and Chen (2011).

Traditionally, bio-inspired design products are an outcome of individual effort. Today, advanced computational methods and tools can also assist engineers in modeling bio-inspired forms. Meanwhile, the advances in fabrication tools can be a catalyst to search optimal and elegant structural form. For example, topology optimization has evolved into a computer-aided technique for modern engineering design and practice. The use of this technique in recent studies (Adriaenssens et al. 2012; Asadpoure et al. 2011; Guest 2009) has helped engineers seek the best distribution of a given amount of material or the optimal geometry of a given domain of structure via an iterative numerical process under specific constraints. An up-to-date summary on recent topology optimization techniques and applications in a variety of disciplines can be found in Deaton and Grandhi (2013).

Nonuniform rational B-Splines (NURBS)-based isogeometric analysis is another geometric numerical modeling technique that optimize the form and the material distribution either in separate or in simultaneous fashions (Bletzinger et al. 2010; Firl and Bletzinger 2012; Nagy et al. 2013; Wall et al. 2008). Other recent case studies on the form-finding techniques support a variety of design innovation on structural forms, which could achieve efficiency, economy, and elegance (Bel Hadj Ali et al. 2010; Bletzinger and Ramm 2001; Burry et al. 2005; Li et al. 2010; Richardson et al. 2013; Xu and Luo 2010).

Another reason for slow pace to meaningful bio-inspired application on the civil infrastructure is the lack of such courses in the engineering curriculum. The good news is that some universities do offer a bio-inspired course to teach students to work in a multidisciplinary environment and learn the principle from nature. For example, a course titled "Exploring Bio-Inspired Systems in Architecture" at the University of Minnesota co-taught by an architecture professor (Marc Swackhamer) and a biology professor (Neil Olszewski).

They followed the traditional architectural teaching approach in terms of design, modeling, and fabrication, but architectural students will receive interesting input from a biology professor that may help them expand their thinking on conceptual design. MIT offered a course in biologically inspired digital design and fabrication course aimed at introducing the emerging interface of engineering and biology and to explore the logic and principles of natural systems through multiscale modeling and experiment. A "Bio-Inspired Design" course at TU Delft gives an overview of nonconventional mechanical approaches in nature and shows how this knowledge can lead to more creativity in mechanical design.

The University of Bath provides a graduate-level course "Biomimetics" to encourage student to extract design principles by introducing a variety of natural materials, structures, and mechanisms. A similar course can also be found at Georgia Institute of Technology. The latest endeavors on teaching and education aspects of promoting bio-inspired studies can be found in many studies (Bruck et al. 2006; Glier et al. 2011; Helms et al. 2009; Jenkins 2011; Santulli and Langella 2011; Stone et al. 2014; Wiltgen et al. 2011).

## 10.4 Summary

The multidisciplinary environment in the design field is pushing engineers to come up with new innovations in structural design. Compared to bio-inspired philosophy in architectural design and mechanical design, the development of bio-inspired design on bridge structures is far behind. This chapter reviewed some recent projects to highlight those endeavors made in this field. It is shown that the bio-inspired method can help engineers address both traditional issues (efficiency, economy, and elegance) and emerging issues (sustainability, energy use, etc.). However, it is noted that most of completed projects only reach a low or middle inspiration level according to the Vincent's biomimetic map. The difficulty of using the bio-inspired method in bridge design is due to the inefficiency of searching biological analogies and the lack of support from a biomimetic researcher during the design process. In modern bridge design, we need more interesting forms for both stationary structures and moveable structures. A close multidisciplinary collaboration may help engineers build more sustainable and smart structural systems for bridges in the twenty-first century.

**Acknowledgments** The authors would like to acknowledge Prof. Pacheco-Torgal for his support and feedback on this chapter and Dr. William C. Taylor, a civil engineering emeritus professor from Michigan State University for checking the language. The authors also appreciate Elsevier and Journal of Bionic Engineering for their reprint permission and Structure for the use of photos.

## References

Adriaenssens S, Ney L, Bodarwe E, Williams C (2012) Finding the form of an irregular meshed steel and glass shell based on construction constraints. J Architect Eng 18(3):206–213. doi:10.1061/(ASCE)AE.1943-5568.0000074

Aldersey-Williams H (2004) Towards biomimetic architecture. Nat Mater 3(5):277–279

Alegria Mira L, Thrall AP, De Temmerman N (2014) Deployable scissor arch for transitional shelters. Autom Constr 43:123–131

Ario I, Nakazawa M, Tanaka Y, Tanikura I, Ono S (2013) Development of a prototype deployable bridge based on origami skill. Autom Constr 32:104–111

Asadpoure A, Tootkaboni M, Guest JK (2011) Robust topology optimization of structures with uncertainties in stiffness—application to truss structures. Comput Struct 89(11–12):1131–1141. doi:http://dx.doi.org/10.1016/j.compstruc.2010.11.004

Bar-Cohen Y (2011) Biomimetics: nature-based innovation. CRC press, Boca Raton

Bar-Cohen Y (2012) Nature as a model for mimicking and inspiration of new technologies. Int J Aeronaut Space Sci 13(1):1–13

Barbarino S, Bilgen O, Ajaj RM, Friswell MI, Inman DJ (2011) A review of morphing aircraft. J Intell Mater Syst Struct 22(9):823–877. doi:10.1177/1045389x11414084

Bel Hadj Ali N, Rhode-Barbarigos L, Pascual Albi AA, Smith IFC (2010) Design optimization and dynamic analysis of a tensegrity-based footbridge. Eng Struct 32(11):3650–3659. doi:http://dx.doi.org/10.1016/j.engstruct.2010.08.009

Bhushan B (2009) Biomimetics: lessons from nature–an overview. Philos Trans Roy Soc A Math Phys Eng Sci 367(1893):1445–1486. doi:10.1098/rsta.2009.0011

Billington DP (1983) The tower and the bridge: the new art of structural engineering. Basic Books, New York

Billington DP (2003) The Art of Structural Design. A Swiss Legacy. Yale University Press, New Haven

Bletzinger K-U, Firl M, Linhard J, Wüchner R (2010) Optimal shapes of mechanically motivated surfaces. Comput. Methods Appl Mech Eng 199(5–8):324–333. doi:http://dx.doi.org/10.1016/j.cma.2008.09.009

Bletzinger K-U, Ramm E (2001) Structural optimization and form finding of light weight structures. Comput Struct 79(22–25):2053–2062. doi:http://dx.doi.org/10.1016/S0045-7949(01)00052-9

Bonser RHC (2006) Patented biologically-inspired technological innovations: a twenty year view. J Bionic Eng 3(1):39–41. doi:http://dx.doi.org/10.1016/S1672-6529(06)60005-X
Bruck H, Gershon A, Golden I, Gupta S, Gyger Jr LS, Magrab E, Spranklin B (2006) New educational tools and curriculum enhancements for motivating engineering students to design and realize bio-inspired products. In: Design and Nature III: Comparing Design in Nature with Science and Engineering, vol 87, p 325
Burry J, Felicetti P, Tang J, Burry M, Xie M (2005) Dynamical structural modeling a collaborative design exploration. Int J Architect Comput 3(1):27–42. doi:10.1260/1478077053739595
Chong KP (2004) Nanotechnology and information technology in civil engineering. In: Paper presented at the towards a vision for information technology in civil engineering
Deaton J, Grandhi R (2013) A survey of structural and multidisciplinary continuum topology optimization: post 2000. Struct Multi Optim, 1–38. doi:10.1007/s00158-013-0956-z
Dollens DL (2005) A system of digital-botanic architecture. Leonardo 38(1):15–21. doi:10.1162/leon.2005.38.1.15
Dooley S (2004). The development of material-adapted structural form. (Ph.D. Dissertation), École polytechnique fédérale de Lausanne
Espinosa HD, Rim JE, Barthelat F, Buehler MJ (2009) Merger of structure and material in nacre and bone—perspectives on de novo biomimetic materials. Prog Mater Sci 54(8):1059–1100. doi:http://dx.doi.org/10.1016/j.pmatsci.2009.05.001
Firl M, Bletzinger K-U (2012). Shape optimization of thin walled structures governed by geometrically nonlinear mechanics. Comput Methods Appl Mech Eng 237–240(0):107–117. doi:http://dx.doi.org/10.1016/j.cma.2012.05.016
Friedman N, Ibrahimbegovic A (2013) Overview of highly flexible, deployable lattice structures used in architecture and civil engineering undergoing large displacements. YBL J Built Environ 1(1):85–103
Gauvreau P (2002) The three myths of bridge aesthetics. In: Developments in short and medium span bridge engineering–2002
Giurgiutiu V (2007) Concepts of adaptronic structures adaptronics and smart structures, pp 9–28. Springer, Berlin
Glier MW, McAdams DA, Linsey JS (2011) Concepts in biomimetic design: methods and tools to incorporate into a biomimetic design course. In: Paper presented at the ASME 2011 international design engineering technical conferences and computers and information in engineering conference
Goel AK, McAdams DA, Stone RB (2014) biologically inspired design: Computational Methods and Tools. Springer
Guest JK (2009) Topology optimization with multiple phase projection. Comput Meth Appl Mech Eng 199(1–4):123–135. doi:http://dx.doi.org/10.1016/j.cma.2009.09.023
Helms M, Vattam SS, Goel AK (2009). Biologically inspired design: process and products. Des Stud 30(5):606–622. doi:http://dx.doi.org/10.1016/j.destud.2009.04.003
Hoult N, Bennett PJ, Stoianov I, Fidler P, Maksimović Č, Middleton C, Soga K (2009) Wireless sensor networks: creating 'smart infrastructure'. In: Paper presented at the proceedings of the ICE-civil engineering
Hu N (2010) The bio-inspired method in design and optimization of bridge structures. (M.S.), Central South University, China
Hu N, Feng P, Dai G (2013) The gift from nature: bio-inspired strategy for developing innovative bridges. J Bionic Eng 10(4):405–414. doi:http://dx.doi.org/10.1016/S1672-6529(13)60246-2
Hurlebaus S, Gaul L (2006) Smart structure dynamics. Mech Syst Signal Process 20(2):255–281. doi:http://dx.doi.org/10.1016/j.ymssp.2005.08.025
Jenkins CH (2011) Doing BiE: Lessons Learned From Teaching Bio-Inspired Engineering. In: Paper presented at the ASME 2011 international mechanical engineering congress and exposition

John G, Clements-Croome D, Jeronimidis G (2005) Sustainable building solutions: a review of lessons from the natural world. Build Environ 40(3):319–328. doi:http://dx.doi.org/10.1016/j.buildenv.2004.05.011
Knippers J, Speck T (2012) Design and construction principles in nature and architecture. Bioinspiration Biomimetics 7(1):015002
Korkmaz S, Ali NBH, Smith IF (2012) Configuration of control system for damage tolerance of a tensegrity bridge. Adv Eng Inform 26(1):145–155
Kovač M (2013) The bioinspiration design paradigm: a perspective for soft robotics. Soft Robot 1(P):28–37
Li Y, Feng X-Q, Cao Y-P, Gao H (2010) A Monte Carlo form-finding method for large scale regular and irregular tensegrity structures. Int J Solids Struct 47(14–15):1888–1898. doi:http://dx.doi.org/10.1016/j.ijsolstr.2010.03.026
Liu K, Jiang L (2011) Bio-inspired design of multiscale structures for function integration. Nano Today 6(2):155–175. doi:http://dx.doi.org/10.1016/j.nantod.2011.02.002
Mak TW, Shu LH (2008) Using descriptions of biological phenomena for idea generation. Res Eng Des 19(1):21–28. doi:10.1007/s00163-007-0041-y
Mattheck C (1998) Design in nature: learning from trees. Springer, Heidelberg
Michaël P, Dominique S (2013) Piezoelectric energy harvesting from traffic-induced bridge vibrations. Smart Mater Struct 22(9):095019
Mudupu V, Trabia MB, Yim W, Weinacht P (2008) Design and validation of a fuzzy logic controller for a smart projectile fin with a piezoelectric macro-fiber composite bimorph actuator. Smart Mater Struct 17(3):035034
Nagel JK, Stone RB (2011) A systematic approach to biologically-inspired engineering design. In: Paper presented at the ASME 2011 international design engineering technical conferences and computers and information in engineering conference
Nagel JK, Stone RB, McAdams DA (2010) An engineering-to-biology thesaurus for engineering design. In: Paper presented at the ASME 2010 international design engineering technical conferences and computers and information in engineering conference
Nagy AP, Ijsselmuiden ST, Abdalla MM (2013) Isogeometric design of anisotropic shells: Optimal form and material distribution. Comput Methods Appl Mech Eng 264(0):145–162. doi:http://dx.doi.org/10.1016/j.cma.2013.05.019
Petra G (2008) The signs of life in architecture. Bioinspiration Biomimetics 3(2):023001
Rhode-Barbarigos L, Hadj Ali NB, Motro R, Smith IF (2010) Designing tensegrity modules for pedestrian bridges. Eng Struct 32(4):1158–1167
Richardson JN, Adriaenssens S, Filomeno Coelho R, Bouillard P (2013) Coupled form-finding and grid optimization approach for single layer grid shells. Eng Struct 52(0):230–239. doi:http://dx.doi.org/10.1016/j.engstruct.2013.02.017
Russell B, Thrall A (2013) Portable and rapidly deployable bridges: historical perspective and recent technology developments. J Bridge Eng 18(10):1074–1085. doi:10.1061/(ASCE)BE.1943-5592.0000454
Santulli C, Langella C (2011) Introducing students to bio-inspiration and biomimetic design: a workshop experience. Int J Technol Des Educ 21(4):471–485. doi:10.1007/s10798-010-9132-6
Sartori J, Pal U, Chakrabarti A (2010) A methodology for supporting “transfer” in biomimetic design. AI EDAM 24(4):483–506
Schlaich M (2004) Future engineering structures for the urban habitat and infrastructure. In: Paper presented at the IABSE symposium report
Shu LH, Ueda K, Chiu I, Cheong H (2011) Biologically inspired design. CIRP Ann Manuf Technol 60(2):673–693. doi:http://dx.doi.org/10.1016/j.cirp.2011.06.001
Singh AV, Rahman A, Sudhir Kumar NVG, Aditi AS, Galluzzi M, Bovio S, Parazzoli D (2012) Bio-inspired approaches to design smart fabrics. Mater Des 36(0):829–839. doi:http://dx.doi.org/10.1016/j.matdes.2011.01.061

Spencer B, Cho S (2011) Wireless smart sensor technology for monitoring civil infrastructure: technological developments and full-scale applications. In: Paper presented at the proceeding of the world congress on advances in structural engineering and mechanics (ASEM'11 Plus)
Srinivasan V, Chakrabarti A, Pal U, Ranjan BSC, Ojha SP, Ranganath R (2011) Supporting process and product knowledge in biomimetic design. Int J Des Eng 4(2):132–158. doi:10.1504/IJDE.2011.045132
Stajano F, Hoult N, Wassell I, Bennett P, Middleton C, Soga K (2010) Smart bridges, smart tunnels: transforming wireless sensor networks from research prototypes into robust engineering infrastructure. Ad Hoc Netw 8(8):872–888
Stephen JE, Christopher AS (2012) The cochlea as a smart structure. Smart Mater Struct 21(6):064001
Stone R, Goel A, McAdams D (2014) Charting a course for computer-aided bio-inspired design. In: Goel AK, McAdams DA, Stone RB (eds) Biologically inspired design, pp 1–16. Springer, London
Tang M-C (2007) Evolution of bridge technology. Paper presented at the IABSE symposium report
Thomas S, Massimilano V, Gunnar T (2012) Design and development of a deployable self-inflating adaptive membrane. In: 53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference. American Institute of Aeronautics and Astronautics
Thrall A, Adriaenssens S, Paya-Zaforteza I, Zoli T (2012) Linkage-based movable bridges: design methodology and three novel forms. Eng Struct 37:214–223
Tomiyama T, Gu P, Jin Y, Lutters D, Kind C, Kimura F (2009) Design methodologies: industrial and educational applications. CIRP Ann Manuf Technol 58(2):543–565. doi:http://dx.doi.org/10.1016/j.cirp.2009.09.003
Trotta MG (2011) Bio-inspired design methodology. Int J Inform Sci 1(1):1–11
Vincent JFV (2001) Stealing ideas from nature. In: Pellegrino S (ed) Deployable structures. Springer, Vienna
Vincent JFV (2006) Applications—influence of biology on engineering. J Bionic Eng 3(3):161–177. doi:http://dx.doi.org/10.1016/S1672-6529(06)60020-6
Vincent JFV, Mann DL (2002) Systematic technology transfer from biology to engineering. Philos Trans Roy Soc Lond Ser A Math Phys Eng Sci 360(1791):159–173. doi:10.1098/rsta.2001.0923
Wall WA, Frenzel MA, Cyron C (2008) Isogeometric structural shape optimization. Comput Methods Appl Mech Eng 197(33–40):2976–2988. doi:http://dx.doi.org/10.1016/j.cma.2008.01.025
Wallner M, Pircher M (2007) Kinematics of movable bridges. J Bridge Eng 12(2):147–153. doi:10.1061/(ASCE)1084-0702(2007)12:2(147)
Wilson JO, Rosen D, Nelson BA, Yen J (2010) The effects of biological examples in idea generation. Des Stud 31(2):169–186. doi:http://dx.doi.org/10.1016/j.destud.2009.10.003
Wiltgen B, Vattam S, Helms M, Goel AK, Yen J (2011) Learning functional models of biological systems for biologically inspired design. In: Paper presented at 11th IEEE international conference on advanced learning technologies (ICALT), 2011
Xing D, Chen W (2011) Systematic method of applying structural characteristics of natural organisms to mechanical structures. Trans Tianjin Univ 17:293–297
Xu X, Luo Y (2010) Form-finding of nonregular tensegrities using a genetic algorithm. Mech Res Commun 37(1):85–91. doi:http://dx.doi.org/10.1016/j.mechrescom.2009.09.003
Yeesock K, Changwon K, Reza L (2010) Novel bio-inspired smart control for hazard mitigation of civil structures. Smart Mater Struct 19(11):115009
Yoseph B-C (2006) Biomimetics—using nature to inspire human innovation. Bioinspiration Biomimetics 1(1):P1