A SIMPLER CABLE STAYED BRIDGE

R. SHANKAR NAIR

BIOGRAPHY

R. Shankar Nair, senior vice president of **exp** US Services Inc. in Chicago, has practiced structural engineering for more than 45 years as a designer, researcher, author, and lecturer. He has a Ph.D. in civil engineering from the University of Illinois at Urbana-Champaign and is licensed to practice engineering in 44 states.

Dr. Nair's design practice encompasses both buildings and bridges. He has designed building structures of up to 90 stories and 1047 ft in height; his bridge designs include what was at the time the longest tied-arch span (909 ft) in the world.

This work has won numerous awards, including four AISC/ NSBA "Prize Bridge" awards, two ACEC "National Grand Awards" and six "Most Innovative Structure" awards from the Structural Engineers Association of Illinois. He has also received a Lifetime Achievement Award and a T.R. Higgins Lectureship Award from AISC.

Dr. Nair is chairman of the AISC Specifications Committee and a former chairman the AISC Task Committee on Stability and the ASCE Committee on Design of Steel Building Structures. He is also a former chairman of the Council on Tall Buildings and Urban Habitat. He was elected to membership in the National Academy of Engineering in 2005.

SUMMARY

Cable-stayed designs are the dominant bridge type today for spans of 800 to 2,000 feet; tied arches are more often the choice in the 500- to 800-foot range. However, as discussed in this paper, simplification of some of the typical features of steel cable-stayed bridges could make them competitive even in the range of spans now dominated by other bridge types.

One possible simplification is to make the concrete deck independent of the strut, in the same way that the deck is independent of the tie in a tied-arch bridge or the lower chord in a truss bridge; this would aid construction and also allow easy deck replacement. Another simplification is to use exposed, unsheathed stay cables of standard galvanized structural strand with standard end fittings, as used in tied-arch bridge hangers; these cables could be readily inspected and, if necessary, replaced.

Yet another simplification is an erection scheme that does not involve balanced cantilever but retains the benefit of not requiring shoring in the navigation span.

All of these unusual features are demonstrated in the trial design and comparison of alternatives for a two-lane river crossing with an overall length of 2,400 ft and a main navigational span of 600 ft.

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Cable-stayed designs are the dominant bridge type today for spans of 800 to 2,000 feet; tied arches are more often the choice in the 500- to 800-foot range. Even in this shorter span range, cable-stayed bridges are competitive in the efficiency of their use of structural materials. However, difficulties related to some of the common features of typical cable-stayed bridges have led many public agencies to be wary of selecting this bridge type when reasonable alternatives are available.

Typical Cable Stayed Bridges

Two of the more common span configurations for cable-stayed bridges are illustrated in Figure 1. In both cases, most of the vertical load on the span is supported by the vertical components of the tension in inclined cables. At the upper ends of the cables, towers or pylons absorb the vertical force components from the cables and transfer them to the foundation. At the lower ends of the cables, the horizontal components of cable tension are absorbed by the deck structure, which acts as a compression strut.

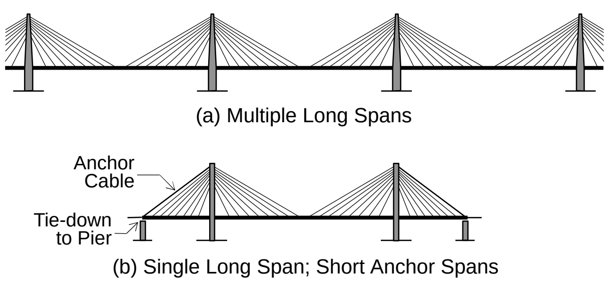

Figure 1. Common Cable-Stayed Span Configurations

When there are multiple long spans (Figure 1a), the cable tension due to span weight will be roughly equal on the two sides of each tower and the horizontal components of the cable tension applied on the tower will be largely in balance; small imbalances can be absorbed by the flexural strength of the towers. With a main span and short side spans (Figure 1b), the larger load on the main span produces larger horizontal forces on the towers toward the main span; these can be balanced by special anchor cables and tie-downs to the foundations at the ends of the outer spans.

In all span arrangements, there may be either two planes of stay cables, one at each edge of the deck, or a single plane of cables along the center with the deck cantilevered out on each side. The deck structure, in all cases, serves as both a compression strut and a stiffening element.

These are just some of the many possible span, tower and cable arrangements in cable-stayed bridges; many other configurations have been used successfully over the years. But while the layout of primary components may vary widely, a few features are shared by most designs: (a) Use of the entire deck structure to serve as the compression strut; (b) enclosed and sealed cables, very difficult to inspect or replace, intended to last the life of the structure; and (c) erection by the balanced cantilever method.

Deck as Compression Strut

Many different deck configurations have been used in cable-stayed bridges; one of the simplest is sketched in Figure 2. It consists of two steel box girders, transverse and longitudinal steel floor framing, and a concrete slab intended to be composite with the steel.

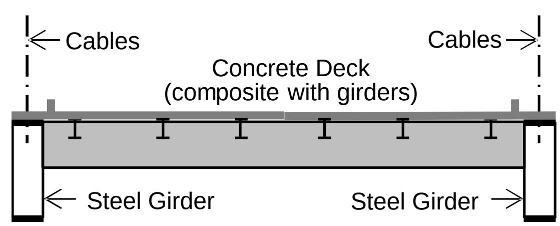

Figure 2. Cross Section—Deck as Strut

Other options include steel or concrete or composite steel/concrete box sections extending across the full width of the deck; for very long spans, these sections are often shaped for aerodynamic benefit.

One feature common to essentially all the designs is that the entire deck structure—longitudinal girders, other longitudinal members, deck slab—

works as a single composite element in resisting the compression induced by the horizontal component of the tension in the cables. This is a very efficient design in its use of materials, but it carries certain penalties.

With the concrete deck slab designed to be part of the compression strut, the balance of forces between girders and slab depends on the erection sequence, which can lead to more or less force being locked into the slab, and varies with time due to creep of the concrete. This leads to a high degree of complexity in design and construction and, most importantly, makes replacement of the concrete deck slab extremely difficult.

Sealed Stay Cables

Many different stay cable designs have been tried and tested over the years, all with the objective of achieving a cable that would stand up to the elements and last the life of the bridge without special maintenance (1, 2, 3).

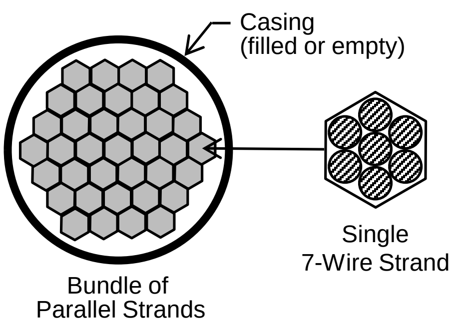

Figure 3. Stay Cable Section

In typical U.S. practice of recent years, the cable, as sketched in Figure 3, consists of many parallel strands within a casing. Each strand is made up of seven high-strength steel wires; in most cases the strand is individually greased or waxed and covered with a high-density polyethylene or high-density poly-propylene extruded sheath. The bundle of strands is sealed in a steel or high-density polyethylene casing, which may be either grouted or empty. (The current trend is toward HDPE casings without fill.)

The end anchorages and jacking systems for the cables are usually proprietary items, designed and tested by the cable manufacturer-supplier.

The record of performance of bridge stay cable systems is mixed. While some have performed well, others have required expensive repair and retrofit, mainly to correct the effects of failures in the corrosion protection system. And even if the most modern cable designs are, in fact, reliable, the difficulty in effectively inspecting and, if necessary, repairing the enclosed cables in service makes some state transportation agencies in the U.S. reluctant to build cable-stayed bridges when reasonable alternatives are available.

Balanced Cantilever Erection

Erection of cable-stayed bridges is usually done by the balanced cantilever procedure: The tower is erected first; then segments of deck structure and cables are added on each side of the tower, in sequence, maintaining balance about the tower.

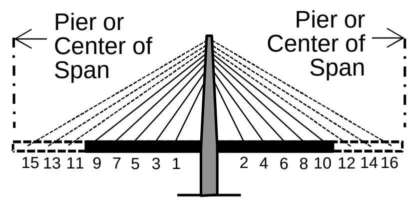

Figure 4. Balanced Cantilever Erection

Balanced-cantilever erection, illustrated in Figure 4, can be very efficient and economical: it does not require shoring; crane picks are modest. However, this method of construction, combined with time-dependent and sequence-dependent effects related to the sharing of compression between the strut and the concrete deck, limits flexibility and requires a high level of specialized engineering sophistication on the part of the builder; this can limit competition and increase cost, at least in the moderate span range.

A Simpler Cable Stayed Bridge

Cable-stayed bridges are very efficient in their use of structural materials. And with a more than 50-year record of performance, most features of modern cable-stayed bridges have been developed to a high degree of refinement. Nonetheless, as discussed, some of these features continue to prove troublesome to many bridge owners and operators. And as a result, cable-stayed designs do not dominate the 500- to 800-ft span range as they do longer spans; tied arches and even trusses are often preferred for highway bridges with spans under 800 ft in the U.S.

To allay these concerns, a simplified cable-stayed bridge design has been developed. It has three features that set it apart from most existing cable-stayed bridges: (a) The deck is independent of the cable-stayed structure; (b) the cables are exposed structural strands; and (c) erection is not by balanced cantilevers.

This simplified cable-stayed concept was developed to a level sufficient to estimate cost and compare with tied-arch and truss alternatives for a two-lane 2400-ft long river crossing with a single navigational span of 600 ft.

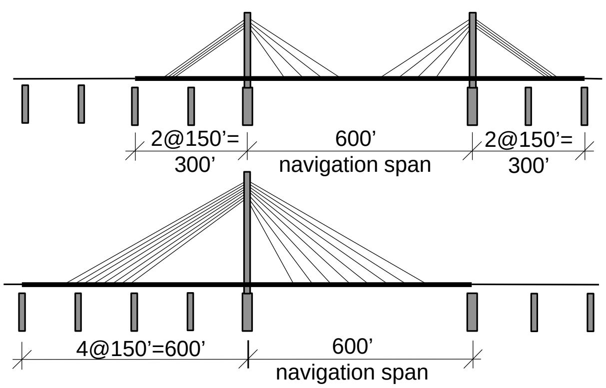

Figure 5. Configurations Considered for the Simplified Cable-Stayed Bridge Designs

As shown schematically in Figure 5, twin-tower and single-tower designs were considered. In both, there is one long navigational span of 600 ft; all other spans (including the "anchor" spans for the cable stays) are 150 ft long. There are no tie-downs of the superstructure to the piers in the anchor spans; instead, ballast is provided as needed (see section on deck).

There are two vertical planes of cables, arranged as shown in Figure 5. The cables are anchored at the top to towers of the shape and height indicated in Figure 6. The towers are of cast-in-place reinforced concrete construction, solid below the elevation of the bridge seat and hollow box sections above that. (Precast and post-tensioned designs could also have been considered for the box-section upper part.)

For all the designs, the concrete deck is 47 ft wide including parapets; the loading is AASHTO HL-93; design is in accordance with the 2012 AASHTO LRFD Specification (4).

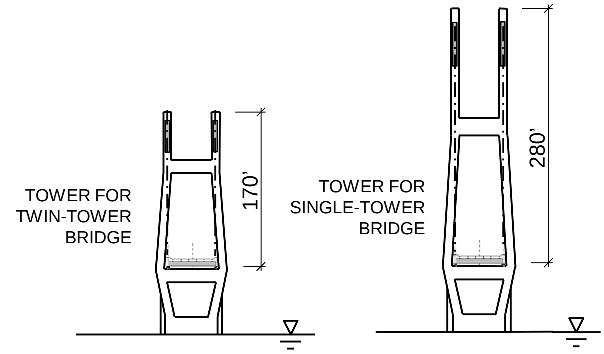

Figure 6. Towers for the Simplified Cable-Stayed Bridge Designs

Presented next is a discussion of each of the special features of the proposed simplified cable-stayed bridge (independent deck, exposed strand cables, simple erection), as applied to the structures in this study.

Independent Deck

In tied-arch and truss bridges, the deck is almost always designed to be independent of the arch tie or truss lower chord; the deck does not work with the arch tie to resist tension or with the truss chord to resist tension or compression. This greatly simplifies construction: there are no locked-in stresses in the deck that would vary with time due to creep or be affected by the construction sequence. It also makes deck replacement a simple and straightforward matter.

The proposed simplification, for the simpler cable-stayed bridge, is to make the concrete deck independent of the strut in exactly the same way that the deck is independent of the tie or truss chord in a tied-arch or truss bridge. The resulting cross section is shown in Figure 7.

The entire compression generated by the horizontal components of cable tension is carried by two steel strut girders of I section. Lateral stability of the girders is not a major issue owing to the fairly close spacing (25 ft) of the transverse floor beams.

The I-section girders have 108-in. deep webs and 24-in. wide flanges; flange thickness varies with a maximum of 2½ in. and 3½ in., respectively, in the twin-tower and single-tower designs. All the steel is ASTM A709 Grade 50.

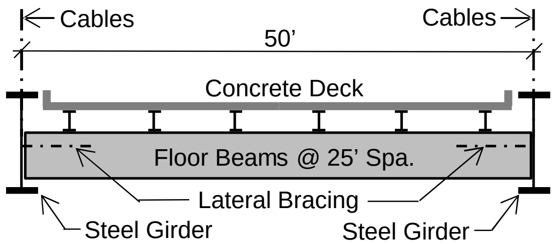

Figure 7. Cross Section—Independent Deck

As shown in Figure 7, the concrete deck is supported on steel W-section stringers that are continuous over floor beams spanning between the strut girders. To further isolate the deck from axial effects in the girders, relief joints are provided across the concrete slab and in the stringers at a spacing of about 300 ft.

Where ballast is needed in the anchor spans, large precast concrete blocks are suspended from the stringers under the deck slab, between the floor beams. (An alternative would be to make the deck slab thicker, by up to about a foot, where extra weight is needed in the anchor spans; this might be more economical than the separate ballast blocks but would carry the penalty of making the deck slab non-standard.)

Overall, the deck-level structure in these cable-stayed designs is very similar to that in the tied-arch design that was considered for comparison; a cross section of the tied-arch option would look virtually identical to Figure 7: The tie girders for the arch are the same as the strut girders for the cable-stayed structure (except for different plate thicknesses in some areas); the concrete deck and stringers and floor beams and lower lateral bracing are very similar. The spacing of tie girders in the tied-arch design is slightly wider (52 ft) to allow space for the ribs to come down past the concrete deck and meet the ties.

The total length of the deck structure shown in Figure 7 is 1,200 ft in both the twin-tower and single-tower designs; this covers both the 600-ft main span and 600 ft of anchor or side spans (see Figure 5).

A feature of this deck structure is that it can span a considerable distance without help from stay cables. This capacity is useful during erection of the bridge.

Exposed Strand Cables

Stay cables for cable-stayed bridges are usually assembled in place from a large number of individual small-diameter (0.5 to 0.6 in. diameter) 7-wire strands as shown in Figure 3. A single strand to carry the entire load in the cable would, typically, be much too large and heavy to fabricate in the shop, wind on a reel, and transport to the site.

For the bridge in this study, however, with its fairly modest 600-ft span, and with the stay cable layout indicated in Figure 5, it was found that each cable (each line in Figure 5) could be a grouping of four approximately 2-in. diameter ASTM A586 galvanized structural strands with standard end fittings picked out of a manufacturer's catalog.

The length of the longest cable is about 300 ft in the twin-tower bridge and 600 ft in the single-tower structure. Even the 600-ft length of 2-in. strand could reasonably be fabricated in the shop, with its end fittings, and transported to the site for erection.

The strand would be installed without enclosure in a sheath or casing; corrosion protection would be provided by the galvanizing on the strand wires (Class A on inner wires, Class C on outer wires). In this regard, the stay cables in the cable-stayed bridge would be no different from the hanger cables in a typical tied-arch bridge.

And as in a tied-arch bridge, the exposed strand could be readily inspected. And if it became necessary, individual strands, with their end fittings, could readily be removed and replaced with the bridge in service. (The stay cable system would be designed with enough redundant capacity to permit this.)

Erection Procedure

The span arrangement (Figure 5) and proposed deck structure (Figure 7) allow a very simple erection procedure. This is illustrated in Figure 8.

There is no need for shoring towers in the main span. Indeed, the entire superstructure erection could be accomplished with minimal work in the main navigational span: The material for construction of the span could be transported over the approach spans and anchor spans, which could be completed first, even including placement of the concrete deck, before any cables are installed. And since the concrete deck does not share in the compression carried by the strut girders, there are none of the time-dependent and sequence-dependent effects that have to be considered in conventional cable-stayed bridge erection.

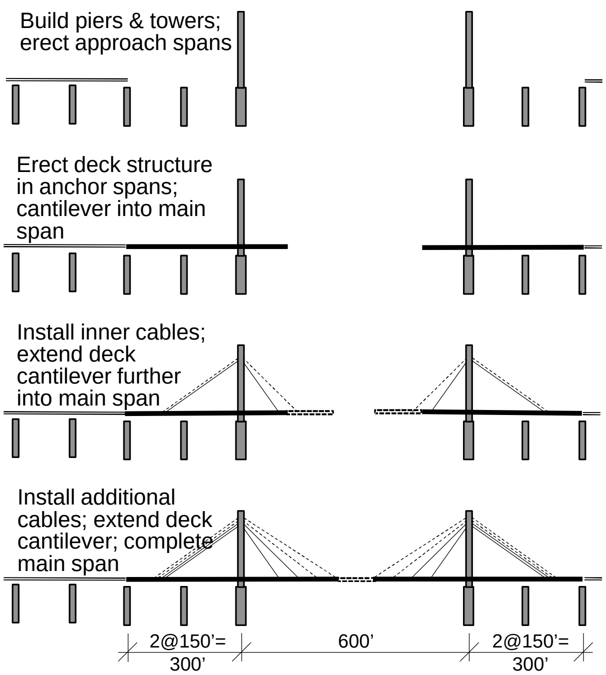

Figure 8. Cable Stayed Bridge Erection Sequence

This simple erection process is made possible in part by the ability of the deck structure (see Figure 7), without stay cables, to cantilever more than 100 ft with the concrete slab in place and more than 150 ft without the slab. This allows deck erection to proceed well ahead of cable installation.

The erection sequence illustrated in Figure 8 is for the twin-tower design. The procedure would be similar for the single-tower design, except that erection would progress from one side (the tower side), not both. Erection from one side alone may be either a benefit or a drawback, depending on project conditions.

Other Alternatives Considered

As noted previously, the simplified cable-stayed designs for the two-lane river crossing with a 600-ft navigational span were compared with a tied-arch design and a truss design. These are illustrated in Figure 9.

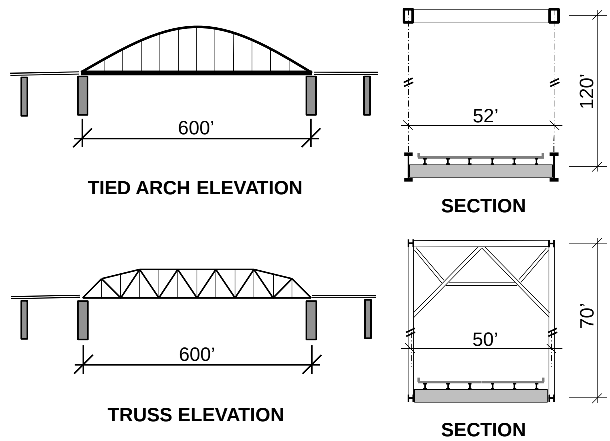

Figure 9. Tied Arch and Truss Designs Considered

The tied arch has a rise of 120 ft. The arch ribs are box sections, 60 in. deep and 42 in. wide; eight transverse struts of box section serve as Vierendeel bracing between the ribs. The tie girders are of I section with 108-in. deep webs and 24-in. wide flanges. The ties are of ASTM A709 Grade 70 steel; all other structural steel is A709 Grade 50. The hangers are A586 galvanized structural strands.

The truss bridge is a single-span through structure with a depth of 70 ft between chord centers. All truss members are welded H sections with flanges vertical, except that highly loaded compression diagonals are welded box sections. All steel is ASTM A709 Grade 50.

The floor system for both the tied-arch and truss bridges (as also for the cable-stayed bridges) consists of a concrete slab on longitudinal W-section stringers supported on transverse welded plate girder floor beams; the floor beams are at hanger location (about 31 ft apart) in the tied-arch bridge and at vertical truss member locations (50 ft apart) in the truss bridge.

For the purposes of this comparison of alternative bridge types, it was assumed that the contractor would be permitted to install falsework towers in the navigational channel for erection of the tied-arch and truss bridges, leaving a clear channel of not less than 300 ft. Erection on falsework is the most economical approach for these bridges. Other options include off-site assembly and float-in (for both arch and truss spans) and erection from temporary erection towers outside the navigational channel (for the arch).

Comparison of Alternatives

The costs and certain other attributes of the simple cable-stayed bridge designs are compared with those of the tied-arch and truss alternatives in Table 1. The total length of the bridge is 2,400 ft and the deck is 47 ft wide (including parapets) in all the designs. There is one main navigational span of 600 ft; all other spans are 150 ft long.

The tied-arch and truss structures are 600 ft long; both cable-stayed structures are 1,200 ft long. The remaining bridge length in each case, to bring the total to 2,400 ft, is made up of 150-ft long approach spans consisting of multiple steel plate girder stringers with composite concrete deck slabs.

The cost noted in the tabulation as "specific to bridge type" for each option includes the cost of 1,200 ft of steel superstructure plus that of that part of the towers that is above the bridge seat elevation in the cable-stayed options. (For the truss and tied-arch designs, 600 ft of approach span superstructure is included with the truss and arch to bring the length to 1,200 ft, to match the 1,200-ft length of the cable-stayed structures.)

The costs "common to all bridge types" include that of the concrete deck, all superstructure elements outside the 1,200 ft included in the previous item, and all piers. The lower parts of the cable-stay towers are assumed to be similar to the main piers in the tied-arch and truss options and are included among the piers as "common to all bridge types" elements. [The cable-stay towers do impose additional forces on the piers they rest on; these forces are, however, swamped by the roughly 4000-kip vessel collision forces for which the piers must be designed, in all options.]

The costs specific to bridge type were estimated in detail; this included sizing of all major components and application of appropriate unit costs. Costs common to all bridge types were estimated less rigorously, on the basis of experience with similar projects. All the cost figures, expressed in current dollars, are intended only for comparison of the alternatives; they do not include contingency allowances and design fees and other soft costs.

The cost comparison shows the "conventional" designs, the tied-arch and truss bridges, to be roughly equal in cost and in the middle of the cost range; the twin-tower cable-stayed bridge costs about 3% less, the single-tower cable-stayed bridge about 3% more.

All these cost figures assume that falsework towers for bridge erection would be permitted in the navigational channel. If this were not so, the costs of the tied-arch and truss bridges would be significantly higher. The twin-tower cable-stayed bridge would then be the most economical option by a wide margin, and even the single-tower design might not be more expensive than the tied-arch or truss bridges.

In all of the attributes other than cost listed in Table 1, the cable-stayed bridges are at least equal to the tied-arch option. The reasons why many transportation agencies are wary of cable-stayed bridges do not apply to the proposed simpler cable-stayed designs: The deck can be replaced as easily as in a tied-arch or truss bridge; the stay cables can be inspected and, if necessary, replaced as easily as the hangers in a tied-arch bridge.

Conclusion

The simpler cable-stayed bridge design presented in this work, with its combination of an independent deck, unsheathed cables, and simple erection, avoids many of the problems and concerns usually associated with this type of bridge. The result is a simple, reliable and economical structure that should extend the range of applicability of steel cable-stayed bridges to the shorter spans now dominated by other designs.

References

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Table 1. Comparative Summary of Attributes

	Truss	**Tied-Arch**	**Cable-Stayed**	
			Twin-Tower	**Single-Tower**
Costs Specific to Bridge Type	$10.5M	$10.8M	$9.5M	$12.2M
Costs Common to all Bridge Types	$27.3M	$27.3M	$27.3M	$27.3M
Total Cost for 2400 ft of bridge (Ratio to lowest)	$37.8M (1.03)	$38.1M (1.04)	$36.8M (1.00)	$39.5M (1.07)
Erection Considerations	Cost assumes falsework towers in channel	Cost assumes falsework towers in channel	No falsework towers in navigation channel	
Inspection	Difficult	Moderate	Moderate	
Painting & Routine Maintenance	Difficult	Moderate	Convenient; all steel except cables readily accessible from deck	
Major Repair or Retrofit	Moderate	Difficult	Moderate	
Deck Replacement	Convenient	Convenient	Convenient	
Design Complexity	Simple	Moderate	Moderate	
Aesthetic Quality	Fair	Good	Good	Excellent