Efficiency and Economy in Bridge and Building Structures

Part 2: A Study for Structural Efficiency and Economy in Construction

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This article references several detailed Tables. Unfortunately, space constraints dictate not reprinting Table 1 from the May 2016 issue of STRUCTURE.

Efficiency and economy of structures are important parts of structural engineering. Efficiency and economy are not new ideas: engineers build many remarkable bridges and buildings under strict financial constraints.

Efficiency for Bridge Structural Systems

Table 2 lists the cost and steel "efficiency coefficients" for suspension and cable-stayed bridges, including most of the longest span bridges in these two categories. In *Table 3* are listed the cost and material efficiency coefficients for different structural bridge systems including representatives for each bridge system. *Table 4* presents the best performance and the margins for the efficiency of the total groups (per this study) of structural systems (in establishing the average data, the highest and lowest coefficients for the group were eliminated). *Table 5* lists the construction-time efficiency for bridges.

Exposed structures like bridges should be elegant: slender with simple forms and should harmonize with the surrounding environment. There is a consensus among engineers and architects that a well-designed structure, using the right structural system, usually results in an elegant and well-proportioned bridge. Also, it is very important that an aesthetically attractive bridge is also efficient and economical.

Even when the challenge was about how to build a bridge with a record span length, the cost of the structure was always an issue that could abort or postpone the project for a long period (the Messina Strait Bridge is a good example). With the progress in structural analysis and software, high-strength properties of available structural materials and improved construction methods, today it is less of a problem to obtain a longer span than ever before. Now the greatest difficulty appears to be securing the needed funding for such projects. For the same reason, engineers start paying more attention to the structural cost because using more efficient systems and technologies allows them to build "more bridge or building" (meaning more built area and longer free-of-column spans).

Different structural systems for bridges have a specific margin of efficiency coefficients for construction materials. For example – steel continuous girders have 2.55 to 3.0 kg/(L x m^2); steel continuous trusses, about 1.8 kg/m^3; chevron portals, 1.20 to 1.50 kg/(L x m^2); cable-stayed, 0.62 to 2.46 kg/(L x m^2); and suspension bridges, 0.62 to 0.98 kg/(L x m^2). The Tables do not include the steel continuous trusses and chevron portals because of very limited information.

Two examples from the author's experience demonstrate the possibilities provided by using the efficiency criteria:

Akashi Kaikyo Bridge, with the longest bridge span of 1991 meters (or 6,532 feet), was completed in 1998. As early as 1988, the author estimated a steel efficiency coefficient of 0.76 for the bridge, based on the limited information about this future structure at that time, using presumed similarity with other suspension bridges already completed in Japan. When, years later near the completion of the bridge, the final technical information for the bridge was made available, the steel efficiency came to 0.83, only 9% difference from the earlier estimate. The result was very close, especially considering that the Akashi Kaikyo Bridge had achieved a new world record with 1.41 times longer span than the previous record holder, the Humber Estuary Bridge. This example proves that an established criterion for bridge (or structure) efficiency can be a powerful tool for designers and developers in preliminary estimates of the material and cost required for new structures, even when new record-long spans are involved.

The replacement of the East Span of the San Francisco-Oakland Bay Bridge occurred from 2002 to 2015. During the period of review and system selection, members of the Engineering Design Advisory Panel (EDAP) for the new bridge, including the author, cautioned transportation authorities about the problems in selecting structural systems. For example, system selection for the "Skyway" and the self-anchored suspension (SAS) for the main span without providing, in advance, construction quantities and costs compared with other bridge systems would be problematic. Of special concern were the high self-weight of the concrete Skyway (resulting in higher seismic forces, heavier piers, and foundations) and the very high cost of the few self-anchored suspension systems built at the time, proposed for the

Table 4. Summary of Bridge Steel, Concrete and Cost Efficiency.

Bridge Structural System	*L* max note 1 meters (feet) min to max	*L* average meters	Steel/Area Average kg/m² (lbs/ft²)	Steel Efficiency kg/m² x L_{av} Best	Steel Efficiency kg/m² x L_{av} Average	Cost/Area Average $/m² ($/ft²)	Cost Efficiency $/m² x L_{av} Best	Cost Efficiency $/m² x L_{av} Average
Suspension Bridges	728 -1,991 (2,388 - 6,532)	1,209	677 (139)	0.62	0.98	11,073 (1,029)	6.51	17.74
Self-Anchored Suspension	112 - 385 (367 - 1,263)	267	1,013 (207)	2.77	5.51	30,044 (2,791)	12.13	83.50
Cable-Stayed Bridges	126 - 1,104 (413 - 3,622)	513	442 (91)	0.62	2.46	6,969 (647)	7.45	35.27
Steel Arch Bridges	130 - 300 (427 - 984)	220	627 (128)	2.48	4.50	5,612 (521)	19.27	39.83
Steel Continuous Bridges	70 - 330 (230 - 1,083)	157	457 (94)	2.55	3.00	1,994 (185)	9.19	14.20
Concrete Arch Bridges	200 - 323 (656 - 1,060)	235	573 (117)	2.52	6.47	5,251 (488)	21.82	51.41
Concrete Continuous Girders	110 - 250 (361 - 820)	179	656 (134)	2.90	5.54	5,068 (471)	12.20	70.39
Concrete Extradosed Bridges	100 - 180 (328 - 591)	132	521 (107)	2.58	4.98	4,727 (439)	20.57	58.84
			Concrete/Area Average m³/m² (yd³/yd²)	Concrete Efficiency m³x10³/m² x L_{av}				
Concrete Continuous Girders	110 - 250 (361 - 820)	179	2.31 (2.53)	6.71	18.43	5,068 (471)	12.20	47.61
Concrete Extradosed Bridges	100 - 180 (328 -591)	131	2.67 (2.93)	9.46	27.58	4,727 (439)	20.57	45.38

Note 1. L max and L average are for the bridges with available data part of this survey and do not include the maximum span lengths achieved with a particular structural system when there is not available information.
Note 2. The best performances (span length, minimum steel or concrete, minimum cost) are highlighted.

suspension portion of the bridge. The authorities ignored the warnings and, as a result, the already high estimated cost escalated to levels making this otherwise elegant bridge one of the most expensive in the world. This escalation is another example that demonstrates how established criteria for efficiency may have saved billions of dollars. As engineers can learn from successfully efficient projects, it is even more important to learn from the mistakes made in large and very expensive projects.

Efficiency for Long-Span and Tall Buildings

Similar to bridges, the efficiency of single-level long-span structures for sports arenas, exhibition halls, aircraft hangars, etc., can be compared using the same efficiency coefficients; an example is given in *Table 6*.

For tall buildings or skyscrapers, a similar approach is used, replacing the span *L* with the height of the building *H*. *Table 7* compares the steel efficiency for such buildings. In both *Tables 6* and *7*, only a few projects are listed to represent the structural systems.

Findings

Based on the best-achieved steel efficiency coefficients, suspension bridges show the best performance (E/E coefficients) with coefficient 0.62 kg/(L x m²); followed by cable-stayed, 0.62 (same as the suspension, but with higher average coefficient); steel continuous and arch, 2.48 – 2.55; concrete continuous and "extradosed", 2.58 –2.90; and concrete arch bridges, 2.52.

Based on cost (economy) coefficients, the suspension bridges are again the best with coefficient $6.51/(L x m²); followed by cable-stayed, $7.45; steel continuous, $9.19; concrete continuous, $12.20; steel arch bridges, $19.27; and concrete arch and "extradosed", $20.57–21.82. Note that the lack of representation of pedestrian bridges in this article's tables is indicative of their cost, as they are often significantly more expensive. For example, Calatrava's Sundial Bridge at Redding, CA, has a cost of $15,670/m². Juan Sobrino provides information for costs per meter square of several pedestrian bridges with spans of 150–200 meters ranging between $16,300/m² and $57,400/m². These costs are significantly higher than costs per m² of suspension and cable-stayed bridges with spans exceeding 500–1000 meters (*Tables 2* and *3*).

The results above are from *Table 3*, where the suspension and the cable-stayed bridges are without competition for the first and second position of most efficient structures. The highest efficiencies for suspension and cable-stayed bridges are valid only for the "classic" types of these structures. Self-anchored suspension bridges and suspended ribbon-decks are not as efficient (*Tables 2* and *3*).

Based on self-weight of the total structure, again the steel suspension, cable-stayed, continuous and arch bridges are more efficient than the remaining systems.

Based on construction time coefficients, the suspension and cable-stayed bridges are built faster than the remaining systems.

Notes

- Suspension and cable-stayed bridges are mostly steel structures, but they are often combined with concrete towers (pylons), composite steel-concrete decks, or both, thus making their rating more difficult.
- The reinforcing and tensioning steel efficiency coefficients (kg per square meter times the average span) used for concrete continuous and "extradosed" bridges (with 40- to 250-meter, or 131- to 820-foot, spans) are more than the steel for longer cable-stayed spans (230 to 890 meters, or 754 to 2919 feet). The coefficients are closer to the steel used for suspension bridges with significantly longer spans (from 720 to 1990 meters, or 2362 to 6528 feet).
- Some recently built bridges in the country, highly acclaimed for their innovativeness and "efficiency", actually exhibit poor performance in cost, materials and construction time efficiency.
- Some "signature" bridges tend to be between the least efficient and least economical; such bridge designs should be used very carefully unless donations from individuals or companies cover the costs and it is not a burden on state or federal budgets.

Conclusions and Recommendations

- The data presented in this article can be used as a start for building a larger "Database" for efficiency of structures and structural systems. A more extensive Efficiency Database will provide very useful information and guidance for total efficiency and its elements: material, cost, construction time, weight for bridges, bridge systems, and other structures. By using the Database, engineers will be able to find the most efficient structures within the system groups and will learn how to further improve their projects based on the specific solutions for these best performance examples. At the same time, engineers will be able to avoid using systems that are significantly less efficient.

- A developed Database will allow engineers to select the most appropriate concept for the overall project, the most important and challenging part of engineering. Economy depends mainly on the design concept.
- The expansion of this Database should be developed with the help of the State Departments of Transportation, design and construction companies, academia and the professional publications for engineers, architects and builders.
- The goal should be to have the Database become a reliable guide for use by professional designers and builders, structural manufacturers, construction managers and owners of bridges and other structures. The use of such a Database can save billions of dollars as early in the process as the selection of the structural system, thus saving necessary funding for construction and renovation of other structures.
- All design and construction of bridges and other larger structure projects with a cost above $30 million, when funded by state or federal budgets (public taxpayer's money), should be awarded only by design (or design-build) competitions. No such project should be approved if the material and cost efficiency coefficients for the project span exceed the typical E/E coefficients for such structures by 20 percent or more.
- In the author's opinion, engineers should monitor their own projects' efficiency, comparing them to industry efficiency averages. This comparison will help engineers discover, at an early stage, whether their project requires adjustments and corrections to remain competitive and provide motivation for further improvement. Being efficient and economical in the design will result in more economical constructions, reduced costs, materials and carbon footprint.

Structural efficiency has become a globally important issue as, in general, efficient constructions with their reduced "carbon footprint" help protect the environment. Concrete, steel, and other materials have significant carbon dioxide emissions released during their production, manufacture and construction. There is no better way for reducing the "carbon footprint" of the construction industry than reducing the quantity of structural materials used in construction.

Given the inherently competitive nature of structural engineering, we may slightly modify the Olympic Games motto, *Citius, Altius, Fortius*, as *Faster, Higher, Stronger, Longer and Lighter*. Thus, to the established competition criteria for higher, longer-span and stronger structures, we can also add those for faster and lighter (less consuming) structures.▪

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Table 2. Steel and Cost Efficiency of Suspension and Cable-Stayed Bridges

Bridge/Location	Year	*L* max	*L* aver.	Area	Steel	Steel/Area	Steel Efficiency	Cost	Cost/Area	Cost Efficiency
		meters (feet)	meters (feet)	$m^2 \times 10^{-3}$	metric tons	kg/m^2 (lbs/ft^2)	$kg/m^2 \times L_{av}$	$M	$/m² $/ft²)	$/m² x L_{av}
Suspension Bridges										
Akashi-Kaikyo, Japan	1998	1,991 (6,532)	1,304 (4,277)	117.3	193,300	1,648 (338)	1.26	4,300	36,658 (3,406)	28.11
Zhoushan Xinoumen, China	2009	1,650 (5,413)	863 (2,830)	59.5	78,152	1,313 (269)	1.52	363	6,098 (567)	7.07
Great Belt East, Denmark	1998	1,624 (5,328)	898 (2,946)	72.7	51,480	708 (145)	0.79	950	13,067 (1,214)	14.55
Runyang, Yangtze, China	2005	1,490 (4,888)	810 (2,657)	83.3	81,300	976 (200)	1.20	256	3,073 (286)	3.79
Humber Estuary, UK	1981	1,410 (4,626)	740 (2,428)	53.7	28,035	522 (107)	0.71	N/A		
Jiangyin, Yangtze, China	1999	1,385 (4,544)	677 (2,221)	65.8	35,300	536 (110)	0.79	200	3,040 (282)	4.49
Verrazano Narrows, NY, USA	1964	1,298 (4,259)	680 (2,230)	128.0	108,864	850 (174)	1.25	320	2,499 (232)	3.68
Hoga Kusten, Sweden	1997	1,210 (3,970)	600 (1,969)	32.0	14,000	438 (90)	0.73	125	3,906 9363)	6.51
Bosporus I , Istanbul, Turkey	1973	1,074 (3,524)	520 (1,706)	58.9	19,020	323 (66)	0.62	N/A		
Severn River, UK	1966	988 (3,241)	533 (1,747)	50.8	16,967	334 (69)	0.63	N/A		
New Tacoma Narrows, WA, USA	2007	853 (2,799)	549 (1,800)	27.1	16,100	594 (122)	1.08	615	22,694 (2,109)	41.36
Carquinez Strait, CA, USA	2003	728 (2,388)	352 (1,155)	28.7	17,322	604 (124)	1.71	220	7,666 (712)	21.78
Bay Bridge Suspension 1936	1936	704 (2,310)	470 (1,543)	118.70	97,161	819 (168)	1.74	N/ Comp.		
Self-Anchored Suspension										
SAS East Span Bay Br. CA, USA	2015	385 (1,263)	285 (935)	37.1	98,600	2,658 (545)	9.33	2,903	78,254 (7,271)	274.58
Sanchaji, China (SAS)	2006	328 (1,076)	197 (647)	24.2	13,182	546 (112)	2.77	58	2,393 (222)	12.13
Sorok, S. Korea	2008	250 (820)	157 (514)	6.2	4,183	674 (138)	4.30	44	7,092 (659)	45.27
Suspended Ribbon										
Lake Hodges, CA, USA	2009	101 (330)	101 (330)	1.4	1,169	810 (166)	8.02	9	6094 (566)	60.34

Cable-Stayed Bridges										
Russky Island, Russia	2012	1,104 (3,622)	171 (562)	65.1	32,720	503 (103)	2.93	NA		
Sutong, China	2008	1,088 (3,570)	563 (1,846)					NA		
Tatara, Japan	1999	890 (2,920)	493 (1,619)	40.00				606	15,150 (1,408)	30.71
Normandie, France	1997	856 (2,808)	493 (1,616)	46.46	20,100	433 (89)	0.88	NA		
Rion-Antirion, Greece	2004	560 (1,837)	450 (1,478)	61.25	31,800	519 (106)	1.15	944	15,404 (1,431)	34.20
Kanchanapisek, Thailand	2007	500 (1,640)	314 (1,029)	29.40	12,011	395 (81)	1.26	84		
J.J. Audubon, USA (TOTAL Steel)	2011	483 (1,583)	291 (955)	22.347	6,735	301 (62)	1.04	NA		
Geogeum, S. Korea	2011	480 (1,575)	223 (732)	20.981	16,387	781 (160)	3.50	244	11,630 (1,081)	52.10
Arthur Ravenel, SC, USA	2005	471 (1,545)	289 (948)	38.582				531	13,763 (1,279)	47.61
Severn, UK	1996	456 (1,496)	217 (713)	33.131	13,953	421 (86)	1.94	NA		
Saint Nasaire, France	1974	404 (1,325)	240 (787)	10.80	5,616	520 (107)	2.17	NA		
Chao Phraya R. Bangkok, Thailand	2006	398 (1,306)	184 (604)	181.21	63,550	351 (72)	1.90	229		
Fred Hartman, TX, USA	1996	381 (1,250)	225 (738)	32.80	5,043	154 (32)	0.68	55	1,677 (156)	7.45
Margaret Hunt Hill, TX, USA	2011	365 (1,197)	250 (820)	21.80				93	4,265 (396)	17.06
Duisburg-Neuenkamp, Germany	1970	350 (1,148)	167 (548)	27.83	9,629	346 (71)	2.08	NA		
Millau Viaduct, France	2004	342 (1,122)	308 (1,009)	63.96	42,100	658 (135)	2.14	377	5,901 (548)	19.19
2nd Dolsan, S. Korea	2012	230 (755)	68 (222)	16.22	5,116	315 (65)	4.67	37	2,250 (209)	33.29
Zakim, Boston, MA, USA	2005	227 (745)	132 (433)	22.27				115	5,163 (480)	39.20
Palma del Rio, Cordoba, Spain	2008	130 (427)	130 (427)	1.95	672	345 (71)	2.65	5	2,505 (233)	19.27
Port of Venice, Italy	2007	126 (413)	116 (379)	9.83	4,170	424 (87)	3.67	29	2,990 (278)	25.89

Table 3. Steel and Cost Efficiency for different Bridge Systems

Bridge/Location	Year	*L* max	*L* aver.	Area	Steel	Steel/Area	Steel Efficiency	Cost	Cost/Area	Cost Efficiency
		meters (feet)	meters (feet)	$m^2 \times 10^{-3}$	metric tons	kg/m^2 (lbs/ft^2)	$kg/m^2 \times L_{av}$	\$M	$\$/m^2$ ($\$/ft^2$)	$\$/m^2 \times L_{av}$
Suspension Bridges										
Akashi-Kaikyo, Japan	1998	1,991 (6,532)	1,304 (4,277)	117.3	193,300	1,648 (338)	1.26	4,300.0	36,658 (3,406)	28.12
Zhoushan Xinoumen, China	2009	1,650 (5,413)	863 (2,830)	59.5	78,152	1,313 (269)	1.52	363.0	6,098 (567)	7.07
Great Belt East, Denmark	1998	1,624 (5,328)	898 (2,946)	72.7	51,480	708 (145)	0.79	950.0	13,067 (1,214)	14.55
Humber Estuary, GB	1981	1,410 (4,626)	740 (2,428)	53.7	28,035	522 (107)	0.71	N/A		
Bosporus I, Istanbul, Turkey	1973	1,074 (3,524)	520 (1,706)	58.9	19,020	323 (66)	0.62	N/A		
Severn River, GB	1966	988 (3,241)	533 (1,747)	50.8	16,967	334 (68)	0.63	N/A		
New Tacoma Narrows, WA	2007	853 (2,799)	549 (1,800)	27.1	16,100	594 (121)	1.08	615	22,694 (2,108)	41.36
Carquinez Strait, CA, USA	2003	728 (2,388)	352 (1,155)	28.7	17,322	604 (123)	1.71	220	7,666 (712)	21.78
Self-Anchored Suspension										
SAS East Bay Br. SF-O CA	2015	385 (1,263)	285 (935)	37.1	98,600	2,658 (544)	9.33	2,902.6	78,254 (7,270)	274.58
Sanchaji, China	2006	328 (1,076)	197 (647)	24.2	13,182	546 (112)	2.77	57.8	2,393 (222)	12.13
Lo Pasador, Ebro River, Spain	2011	112 (367)	83 (273)	5.0	2,215	444 (91)	5.33	18.9	3,788 (352)	45.45
Suspended Ribbon										
Lake Hodges, CA	2009	101 (330)	101 (330)	1.4	1,169	810 (166)	8.05	8.8	6,094 (566)	60.59
Cable-Stayed Bridges										
Tatara, Japan	1999	890 (2,920)	493 (1,619)	40.00				606	15,150 (1,407)	30.71
Normandie, France	1997	856 (2,808)	493 (1,616)	46.46	20,100	433 (89)	0.88	NA		
Rion-Antirion, Greece	2004	560 (1,837)	450 (1,478)	61.25	31,800	519 (106)	1.15	943.5	15,404 (1,431)	34.20
Arthur Ravenel, SC	2005	471 (1,545)	289 (948)	38.582				531	13,763 (1,279)	47.61
Fred Hartman, TX	1996	381 (1,250)	225 (738)	32.80	5,043	154 (31)	0.68	55	1,677 (156)	7.45
Millau Viaduct, France	2004	342 (1,122)	308 (1,009)	63.96	42,100	658 (135)	2.14	377.4	5,901 (548)	19.19
2nd Dolsan, S. Korea	2012	230 (755)	68 (222)	16.22	5,116	315 (64)	4.67	36.50	2,250 (209)	33.29
Steel Continuous Girders										
Rio-Niteroi, Guanabara, Brazil	1974	300 (984)	233 (765)			596 (122)	2.55	NA		
Great Belt E Appr., Denmark	1997	193 (633)	181 (593)	63.48	31,000	488 (100)	2.70	NA		
Bebresh 2, Hemus, Bulgaria	1986	162 (531)	121 (396)	9.92	4,300	433 (89)	3.59	NA		
Ch. Bond, MO	2008	140 (460)		10.84	N/A			30.00	2,768 (257)	19.74
Lavis, Italy	2008	120 (394)	71 (232)	21.650	4,500	208 (43)	2.94	29.40	1,358 (126)	19.21
New DeSoto, MN	2009	105 (345)	80 (263)	7.939	N/A			7.28	917 (85)	11.44
Steel Cantilevered Trusses Bridges										
Minato, Osaka, Japan	1973	510 (1,673)	328 (1,075)	44.24	35,900	811 (166)	2.48	NA		
Bay Bridge SFO, CA, 1936	1936	427 (1,400)	245 (805)	27.832	20,412	733 (150)	2.99	N Comp.		
Steel Arch (Tied Arch) Bridges										
Nanning Butterfly, China	2009	300 (984)	137 (448)	18.71	10,020	536 (110)	3.92	88.00	4,703 (437)	34.41
Ohio River, OH	2008	268 (879)	268 (879)	8.20	5,443	664 (136)	2.48	N/A		
Tri-Country Pedestr.,Ge/Fr/Sw	2007	229 (753)	83 (271)	1.50	1,020	680 (139)	8.22	11.88	7,920 (736)	95.77
Bridge on Loire, France (Calatrava)	2000	202 (661)	202 (661)	9.73	5,350	550 (113)	2.73	38.00	3,905 (363)	19.37
Palma del Rio, Spain	2008	130 (427)	130 (427)	1.95	672	345 (71)	2.65	4.88	2,505 (233)	19.27

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Table 3. Steel and Cost Efficiency for different Bridge Systems (continued)

Bridge/Location	Year	L max	L average	Area	Concrete/ Reinf. Steel	Concrete R. Steel	Concrete / R. Steel Efficiency	Cost	Cost/Area	Cost Efficiency
Concrete		meters (feet)	meters (feet)	$m^2 \times 10^{-3}$	m^3	m^3/m^2 (yd^3/ft^2)	$m^3x10^{\wedge 3}/m^3$	$M	$\$/m^2$	$\$/m^2 \times L$
Reinforcing Steel		meters (feet)	meters (feet)	$m^2 \times 10^{-3}$	metric tons	kg/m^2 (lbs/ft^2)	kg/m^3	$M	$\$/ft^2$	$\$/m^2 \times L$
Concrete Continuous Girders Bridges										
Northumberland Str. Canada	1997	250 (820)	250 (820)	2.93	4,909.2	1.68 (0.20)	6.71	N/A		
Metsovo Bridge, Greece	2009	235 (771)	164 (539)	14.46	50,700	3.51 (0.43)	21.34	42.12	2,912 (271)	17.73
same steel		235 (771)	164 (539)	14.46	9,520	658.23	4.01			
Benicia-Martinez, CA	2007	201 (659)	162 (532)	54.36	N/A			858.80	15,798 (1,468)	97.35
East Bay Bridge, SF-O, CA	2013	160 (525)	160 (525)	122.73	342,400	2.79 (0.34)	17.44	1426.40	11,622 (1,080)	72.64
Skyway same steel	2013	160 (525)	160 (525)	122.73	199,946	1,629	10.18			
Beauharnois, Montr., Canada	2012	150 (492)	61 (199)	65.31	95,000	1.45 (0.18)	23.95	275.00	4,211 (391)	69.33
same steel	2012	150 (492)	61 (199)	65.31	36,500	559	9.20			
New Minneapolis Br., OH	2008	154 (504)	109 (359)	23.16	37,234	1.61 (0.20)	14.71	234.00	10,103 (939)	92.44
same steel	2008	154 (504)	109 (359)	23.16	9,927	428.61	3.92			
Concrete Extradosed (Cable-Stayed) Bridges										
Danube II, Vidin-Kalafat	2013	180 (591)	106 (348)	30.09	120,000	3.99 (0.48)	37.56	328.08	10,902 (1,013)	102.70
Romania-Bulgaria same steel	2011	180 (591)	106 (348)	30.09	28,300	940 (193)	8.86			
Teror Viad,Gr.Canaria, Spain	2011	145 (476)	87 (285)	2.74	7,300	2.66 (0.32)	30.62	8.40	3,065 (285)	35.23
same steel	2011	145 (476)	87 (285)	2.74	1,230	449 (92)	5.16			
Yumekake, Japan concrete	2010	127 (417)	123 (403)	4.03	17,111	4.25 (0.52)	34.57	40.67	10,101 (938)	82.16
same steel	2010	127 (417)	123 (403)	4.03	2,731	678 (139)	5.52			
Povazka Bystrica, Slovakia	2010	122 (400)	96 (314)	22.52	20,420	0.91 (0.11)	9.46	57.00	2,531 (235)	26.42
same steel	2010	122 (400)	96 (314)	22.52	13,293	590 (121)	6.16			
Extrados, Slovenia concrete	2007	100 (328)	100 (328)	6.15	9,488	1.54 (0.19)	15.43	12.65	2,057 (191)	20.57
same steel	2007	100 (328)	100 (328)	6.15	1,589	258 (53)	2.58			
Concrete Arch Bridges										
Hoover Dam Bypass, NV	2010	323 (1,060)	72 (237)	15.52	N/A			114.00	7,345 (682)	101.47
Gangou Bridge, China	2013	250 (820)	90 (295)	7.56	22,937	3.03 (0.37)	33.71	18.90	2,500 (232)	27.78
(hybrid arch br.) same steel		250 (820)	90 (295)	7.56	6,638	878 (180)	9.76			
Svinesund Bridge, Norway	2005	247 (811)	110 (360)	15.49	9850	0.64 (0.08)	5.80	98.55	6,363 (591)	58.04
same steel		247 (811)	110 (360)	15.49	7,430	480 (98)	4.38			
Reggio Emilia, Italy	2007	218 (715)	77 (252)	5.84	11,000	1.88 (0.23)	24.56	24.30	4,160 (386)	54.25
same steel		218 (715)	77 (252)	5.84	4,000	685 (140)	8.93			
Krka, Croatia	2005	204 (669)	89 (293)	7.56	12,000	1.59 (0.19)	17.77	16.20	2,143 (199)	23.99
same steel		204 (669)	89 (293)	7.56	1,700	225 (46)	2.52			
Maslenica, Croatia	1997	200 (656)	87 (284)	7.14	16,500	2.31 (0.28)	26.66	13.50	1,891 (176)	21.82
same steel		200 (656)	87 (284)	7.14	N/A					

Table 5. Construction Time Efficiency of Bridges

Bridge	Year	*L* max	*L* average	Area	Constr. Time	Time/Area	Constr. Time Efficiency
		L max	L_{av}	*A*	T	T/*A*	T/(*A* x L_{av})
		meters (feet)	meters (feet)	$m^2 \times 10^{-3}$	days	days x $10^3/m^2$	days x $10^6/m^2$xL
Suspension Bridges							
Akashi-Kaikyo, Japan	1998	1,990 (6,529)	1,304 (4,277)	117	3,468	30	22.67
Zhoushan Xinoumen, China	2009	1,650 (5,413)	863 (2,830)	60	1,642	28	31.96
Great Belt East, Denmark	1998	1,624 (5,328)	898 (2,946)	73	2,555	35	39.14
Runyang, Yangtze, China	2005	1,490 (4,888)	810 (2,657)	83	1,643	20	24.34
Humber Estuary, GB	1981	1,410 (4,626)	740 (2,428)	54	3,042	57	76.54
Verrazano Narrows, NYC, NY	1964	1,298 (4,259)	680 (2,230)	128	1,825	14	20.97
Golden Gate, San Francisco, CA	1937	1,280 (4,200)	655 (2,150)	54	1,612	30	45.64
Hoga Kusten, Sweden	1997	1,210 (3,970)	600 (1,969)	32	1,460	46	76.04
Mackinac, USA-Canada	1957	1,158 (3,799)	752 (2,467)	39	1,278	33	43.45
Bosporus I, Istanbul, Turkey	1973	1,074 (3,524)	520 (1,706)	59	1,369	23	44.70
Severn River, GB	1966	988 (3,241)	533 (1,747)	51			
New Tacoma Narrows, WA	2007	853 (2,800)	549 (1,800)	27	1,460	54	98.23
Carquinez Strait, CA	2003	728 (2,388)	352 (1,155)	29			
Bay Bridge, SF, CA, 1936	1936	704 (2,310)	265 (869)	249	1,278	5	19.36
Ambassador, MI	1929	564 (1,850)	370 (1,213)	41	786	19	51.65
Bay Bridge, SF, CA 2015	2015	385 (1,263)	178 (582)	184	5,020	27	153.94
Lake Hodges, San Diego, CA	2009	101 (330)	101 (330)	1	608	422	4,182.71
Cable-Stayed Bridges							
Sutong, Yangtze, China	2008	1,088 (3,570)	563 (1,846)	71	1,095	15	27.25
Stonecutters, Hong Kong	2010	1,018 (3,340)	393 (1,288)	62	2,099	34	85.91
Tatara, Japan	1999	890 (2,920)	477 (1,564)	40			
Normandie, Seine, France	1997	856 (2,808)	493 (1,616)	46	1,661	36	72.58
Rion-Antirion, Greece	2004	560 (1,837)	450 (1,478)	61	1,643	27	59.54
Kanchanapisek, Thailand	2007	500 (1,640)	314 (1,029)	29			
Arthur Ravenel Jr., SC	2005	471 (1,545)	289 (948)	182	1,460	8	80.08
Bay Chay, Vietnam	2006	435 (1,427)		21			
Saint Naser, France	1976	404 (1,325)	240 (787)				
Fred Hartman, TX	1996	381 (1,250)	225 (738)	33			
Millau Viaduct, France	2004	342 (1,122)	308 (1,009)	63	1,156	18	59.33
Samuel Beckett, Dublin, Ireland	2009	123 (404)	123 (404)		943		
Jianshe (SAS), China	2008	110 (361)	67 (219)	5	456	84	1,257.41

Concrete Continuous (Precast Segmental) Bridges							
Bay Bridge, SF, CA, 2015	2,013	160 (525)	160 (525)	106	4,380	41	258.06
4th Street, Pueblo, CO	2,011	115 (378)	85 (279)	11	1,217	115	1,353.24
Kealakaha Stream, HI	2,010	110 (360)	73 (240)	3	1,125	351	4,792.85
Route 36 Highland, NJ	2,010	71 (232)	55 (179)	14	1,095	80	1,457.49
Bellair Beach, FL	2,009	54 (177)	33 (108)	21	1,004	48	1,451.05
Sept. 11 Memorial, NJ	2,008	37 (120)	37 (120)	6	958	150	4,115.87
Concrete Continuous Bridges							
New Minneapolis, MN	2,008	154 (504)	109 (359)	23	322	14	127.34
Concrete Arch Bridges							
Hoover Dam, NV-AZ	2,010	323 (1,060)	193 (634)	16	2,023	130	674.13
Concrete Extradosed (Cable-Stayed) Bridges							
Sunniberg Bridge, Switzerland	2,005	140 (459)	105 (345)	5	1,159	245	2,329.20
Povazka Bystrica, Slovakia	2,010	122 (400)	122 (400)	23	639	28	232.49
"Extrados" Bridge, Slovenia	2,007	100 (328)	100 (328)	6	578	94	939.99

Table 6. Steel Efficiency for Long-span Roof Structures

Roof System	Building	Location	*L* or (L1 x L2)	*L* or (L1 x L2)	*L* max or *L* average	*L* max or *L* average	Steel/Area	Steel Efficiency
			meters	feet	meters	feet	kg/m^2 (lbs/ft^2)	$kg/m^2 \times L_{av}$
Suspension Systems								
One-layer Cable [2]	Madison Square Garden	New York, USA	125	410	125	410	120 (25)	0.96
One-layer Cable	Exposition Hall	Oklahoma, USA	122x97	400x318	109.5	359	25 (5)	0.23
Membrane	Sport Arena	Moscow, Russia	224x183	735x600	203.5	668	105 (22)	0.52
Membrane	Sport Arena	St. Petersburg, Russia	160	525	160	525	111 (23	0.69
Bicycle Wheel	Sport Arena, project	Sofia, Bulgaria	135	443	135	443	36 (7.4)	0.27
Membrane	Coliseum	Arizona, USA	116	381	116	381	32 (6.6)	0.28
Membrane	Stadium	Vienne, Austria	112	367	112	367	45 (9)	0.40
Cable (one-way)	Sport Arena	Stockholm, Sweden	102	335	102	335	28 (6)	0.27
Truss (suspension)	Johaneshof	Stockholm, Sweden	82	269	82	269	7 (1.4)	0.09
Truss (suspension)	Phoenix	Arizona, USA	213x78.5	699x258	145.9	479	294 (60)	2.02
Domes								
Rib Dome	Astrodome	Huston, TX, USA	224x196	735x643	210	689	95 (19)	0.45
Rib Dome	Superdome	New Orleans, USA	207	679	207	679	75 (15)	0.36
Geodesic Dome	Exposition Hall	Tokyo, Japan	120	394	120	394	80 (16)	0.67
Geodesic Dome	Repair Facility	Louisiana, USA	114	374	114	374	56 (11)	0.49
Dome Aluminum	Festival Hall	London, UK	109	358	109	358	69 [3] (14)	0.63
Trusses								
Two-way	Hangar	Switzerland	129	423	129	423	200 (41)	1.55
One-way	Coliseum	Edmond, Canada	122	400	122	400	123 (25)	1.01
One-way	Exposition/sport Hall	Cleveland, Ohio, USA	102	335	102	335	182 (37)	1.78

Notes: 1. The suspension and dome systems are on round or oval bases and the L max is the diameter for round bases or the average diameter for oval bases. L1 and L2 are respectively the long and short dimension of an oval base.
2. The Madison Square Garden structural system is suspension "braced" against uplift with self weight ballast
3. 69 kg/m^2 is the aluminum weight per m^2 scaled to steel weight

Table 7. Steel Efficiency of Tall Buildings

Building	Location	Year	Height (*H*)		Structural Steel/Area	Steel Efficiency
			meters (feet)	Stories	kg/m^2 (lbs/ft^2)	$kg/(m^2 \times H)$
Sears Tower	Chicago, USA	1974	443 (1,453)	109	160 (33)	0.36
WTC*	New York, USA	1973/2001	411 (1,348)	110	205 (42)	0.50
Empire States	New York, USA	1930	381 (1,250)	102	220 (45)	0.58
Standard Oil	Chicago, USA	1973	343 (1,125)	82	160 (33)	0.47
John Hancock	Chicago, USA	1970	337 (1,106)	100	145 (30)	0.43
Chrysler	New York, USA	1930	319 (1,047)	68	160 (33)	0.50
First Bank	Chicago, USA	1970	275 (902)	72	180 (37)	0.65
Steel Corporation	Pittsburg, USA		256 (840)	70	150 (31)	0.59
Man-Montparnasse**	Paris, France	1972	210 (689)	58	100 (20)	0.48
WTC*	WTC towers were destroyed on 9/11 2001 by a terrorist attack					
Man-Montparnasse**	A building with concrete core					