Structural art: John S. Eastwood and the multiple arch dam

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In his landmark book The Tower and the Bridge, engineering professor/historian David Billington proposes the concept of ‘structural art’ and, with a focus on bridges, thin shell roofs and tall buildings, describes its relationship to the ideals of efficiency, economy and elegance. Dams are not discussed in The Tower and the Bridge, apparently because the massive gravity designs commonly built for major projects represent bulky, inefficient designs. Moving beyond gravity dam technology, this paper explores how John S. Eastwood’s work designing multiple arch dams accords with Billington’s idea of structural art. Eastwood built the world’s first reinforced concrete multiple arch dam at Hume Lake, California in 1908 and during the last 15 years of his life became a prominent proponent of the technology. Eastwood’s designs, how they correlate to the ideals of efficiency, economy and elegance, and how he integrated mathematical theory into his design methodology comprise the focus of this paper. In addition, issues of visual appearance and their effect upon professional acceptance of Eastwood’s design are also considered. By employing the concept of structural art as a prism for studying multiple arch dams, the article elucidates an important aspect of hydraulic engineering history.

I. INTRODUCTION

In his landmark book The Tower and the Bridge, engineering professor/historian David Billington proposes the concept of ‘structural art’ in the hope it will further understanding—and appreciation—of innovative structural design.1 Recognising that the Industrial Revolution provided engineers with copious quantities of iron, steel and reinforced concrete that could foster forms far different from those possible using traditional methods of timber, stone and masonry construction, Billington’s conception of structural art is visually oriented but extends beyond the context and concerns of traditional architectural analysis.2 Uninterested in assimilating the work of famed engineers such as Thomas Telford, John Roebling, Gustave Eiffel, Robert Maillart, Othmar Ammann, Eugene Freyssinet, Heinz Isler and Christian Menn into a conventional rendering of design history, Billington has developed a means of analysing the structural validity and visual significance of bridges, long span roofs, tall buildings, dams and so on, independent of architectural theory. To Billington, the practice of structural engineering constitutes a creative endeavour which, purely on its own terms, can produce socially useful works of art on a monumental scale.

In addition to differentiating engineering from architecture, Billington also demarks engineering as more than applied science. Reacting to notions that technology represents little more than an application of scientific principles and mathematical formulae, he bristles at the idea that ‘creative genius and the precedence in innovation belong to the scientist; the engineer is merely the technician, following orders from above.’3 Perceiving the ascendance of scientific and mathematical theory in the early 20th century as often working against creation of innovative design, Billington believes that the intelligent use of simple mathematical formulations is often better than reliance upon complicated (and seemingly more precise) formulae. As he phrases it, ‘the leading scientific idea [associated with structural art] might be stated as that of reducing analysis... and [resisting the] tendency to overemphasize analysis... When the form is well chosen its analysis becomes astoundingly simple.’4

For Billington, the first ideal of structural art is efficiency, for without efficient use of materials a structure cannot exhibit the lightness necessary to distinguish it from ponderous, masonry-derived forms.5 Clearly, if a structure contains excessive material that does little or nothing to add to its strength, then it cannot be an efficient design. The beauty of structural art is dependent upon design that uses as little material as possible; conversely, designs that are profligate in their use of material or utilise decorative features in order to make them more ‘attractive’ or ‘architectural’ are anathema to the concept.

The second ideal is economy. Although the economic advantages of a design often derive from efficient use of material, it is not always true that material conservancy leads inevitably to economic savings. For example, in a reinforced concrete structure costs correlate with the amount of cement, aggregate and steel reinforcement used. Costs, however, also depend upon both the complexity of wooden formwork and expenses involved in mixing, conveying and casting concrete. In adhering to economy as an ideal, structural art separates itself from fanciful public sculpture (as attractive as it might be) and connects with the economic concerns of financiers, stockholders, investors, taxpayers and so on. By definition, structural art must be of practical, civic use to society and must not waste scarce economic resources.
The third ideal is elegance. Although difficult to define in unambiguous terms, the relationship between elegance and structural art is of key importance. The creation of structural art requires consideration of visual qualities, but in a manner that does not simply mimic or expropriate architectural motifs. Of course, the beauty of a design is not a quantifiable attribute and personal preferences will vary from one observer to another. However, a structural artist integrates an aesthetic sensibility into the design process and the creation of structural art depends upon more than a mechanic search for efficient, economic design.

2. DAMS AND STRUCTURAL ART

Given the numerous examples of structural art discussed in The Tower and the Bridge (they extend from Telford’s 1814 Craigellachie Bridge in Scotland through Christian Menn’s 1980 Ganter Bridge in Switzerland) it is noteworthy that dams were excluded from consideration. Although dams clearly contribute to the public works infrastructure responsible for fostering structural art, their absence from Billington’s analysis does not appear to be the result of hasty oversight. Rather, it relates to the predilection of many dam engineers to depend upon traditional methods of design in the construction of water storage structures. Ancient techniques of piling up timber, earth, rock, and masonry constitute the conceptual foundation of the modern gravity dam. And, beginning with the work of the French engineers de Dezilly and Delocre in the 1850s, mathematically based methods of gravity dam design have always relied upon material bulk to provide stability. The form of masonry and concrete gravity dams is directly related to an ‘aesthetic of mass’ and bears little relevance to Billington’s concept of structural art. Furthermore, while examples of arch dams (i.e. curved structures with a cross-sectional profile too thin to provide stability as a gravity dam) date back to ancient times and were present in the 19th century (e.g. the 1854 Zola Dam in France and the 1884 Bear Valley Dam in California), designs of this type—with expansive downstream façades— are frequently quite similar in appearance to curved gravity dams.

Thin arch dams can no doubt be efficient in their use of material compared with gravity designs, but nonetheless they often project a massive appearance making it difficult for observers visually to differentiate them from the more predominant gravity dam technology.

In the United States, major concrete gravity dams built by the Bureau of Reclamation (Figure 1) and the Tennessee Valley Authority (Figure 2) have garnered most attention devoted to the aesthetics of water storage design. Such analyses generally accept that gravity dams comprise a suitably economic form and then proceed to assess and/or praise their architectural embellishments. For example, the prominent architectural historian Carl Condit proclaimed that Fontana Dam, a large gravity structure containing more than 2 million m$^3$ of concrete and featuring moderne surface treatments, to be ‘a classic of the structural art, a perfect symbol of man and nature in harmony.’ Here, Condit does not use the term ‘structural art’ as Billington would, but he does ascribe to massive concrete gravity dams a special artistic character and to the massive Fontana Dam in particular the distinction of being a ‘perfect symbol’ conjoining humans and nature. Given that most major 20th century dams utilised massive embankments or massive masonry/concrete gravity designs it is not so surprising that Condit’s perspective has held sway and that the structural art of dams as Billington would define it seems almost an oxymoron.

In The Tower and the Bridge Billington presents no argument denying the possibility of reconciling his concept of structural art with dam design, but no obvious examples appeared available for analysis. As a result, no dam designs or dam engineers were discussed. This article represents an effort to explain how dam engineering can logically be brought under the umbrella of structural art. In particular, it demonstrates how the work of John S. Eastwood in developing the multiple arch dam, a technology predicated upon minimising the amount material required to impound a reservoir, conforms especially well to the concept of structural art.

3. EASTWOOD AND STRUCTURAL ART

In classic form, the upstream face of the multiple arch dam consists of a series of cylindrical arches. These thin arches are supported on buttresses that, depending upon the site and the
Even more striking, the 516 m long concrete multiple arch dam at Hume Lake in California’s Sierra Nevada (18·6 m high to the deepest foundation, 206 m long). He quickly followed with construction of the 28 m high Big Bear Valley Dam in Southern California completed in 1911 (Figures 3 and 4) and continued innovating with the technology until his death at the age of 67 in August 1924.

During his life, 17 of Eastwood’s dams were built and he developed plans for more than 40 other sites and projects in the American West, Canada and Mexico. However, his work was never embraced by America’s engineering establishment (the prominent hydraulic engineer and gravity dam advocate John R. Freeman—who served as president of both the American Society of Civil Engineers (ASCE) and the American Society of Mechanical Engineers (ASME)—was particularly adamant in opposing Eastwood’s multiple arch designs). After his death Eastwood received little recognition for his innovative accomplishments. Taking Eastwood’s designs and analysing them through the prism of structural art provides a useful means of extending Billington’s idea into the realm of hydraulic engineering; just as importantly, it focuses attention on the professional forces that influence the practice of structural engineering.

Born of Dutch heritage in Minnesota in 1857, Eastwood attended the University of Minnesota between 1877 and 1880 and took classes in the ‘Scientific Course.’ Before graduating he left to work on the Northern Pacific Railroad for three years and then migrated to California where he practiced civil engineering until the end of his life. In California, Eastwood’s career involved three distinct phases

(a) general civil engineer/surveyor (1883–1894)
(b) hydroelectric power engineer (1895–1907)

(c) dam design engineer (1908–1924).

His work building the San Joaquin Electric Company’s hydroelectric power system in 1895–96 (430 m head, 60 km-long, 11 000 volt transmission line) and his design of the one million horsepower capacity Big Creek hydropower system (between 1902 and 1907) comprised major engineering achievements, but he did not begin building multiple arch dams until he was 51 years old. From 1908 onwards his development of the technology was continuous and his most advanced designs were not conceived until he was over 60. Significantly, this career path accords with the experience of many other structural artists as Telford did not design his first modern arch until he was 53, John Roebling designed the Brooklyn Bridge when he was over 60 and Maillart created his Salginatobel arch bridge masterpiece at age 56.

4. EFFICIENCY

From the beginning of his work as a dam design engineer, Eastwood championed efficiency as the basic tenet of his designs and promoted multiple arch dams because of their ability to reduce concrete quantities while keeping safety factors high. Or, as he succinctly phrased it in a 1915 promotional pamphlet distributed to prospective clients: ‘Bulk Does Not Mean Strength.’ Compared with concrete gravity dams, multiple arch dams are generally much more efficient. Eastwood’s cave creek dam featured 12 arches each spanning 9·75 m; they vary in thickness from 0·3 m at the top to 0·75 m in the deepest foundations (Water Resources Center Archives)
interest lay in creating reservoirs high in the Sierra Nevada for hydroelectric power projects. Here, transportation costs were high, encouraging designs that reduced cement haulage. Once he had developed the basic structural form, however, he appreciated that multiple arch designs were suitable for a wide variety of sites, no matter how accessible. Early on he came to characterise the multiple arch dam as ‘The Ultimate Dam,’ but he continually innovated in seeking more efficient forms.\(^{23}\) Analysing the relationship between depth of excavation to reach bedrock, dam height, site width, buttress spacing, buttress slope, arch span, and arc of arch for a wide variety of dam site openings, he discerned that no single design template could serve all purposes.\(^{24}\) Of course, he often worked from earlier designs when developing estimates for new projects, but he never stopped trying to find new ways to reduce concrete quantities.

For example, in 1918 he conceived of ‘radial plan’ designs featuring angled (not parallel) buttresses that minimised the arch radius where hydrostatic pressure is greatest (Figure 5). With a variable radius, each conical (not cylindrical) arch is thinner in the lower sections of the dam, significantly reducing concrete quantities.\(^{25}\) Unfortunately for Eastwood, his radial plan design encountered significant opposition (visually it appeared to be curved the wrong way, downstream rather than upstream) and none was ever built.\(^{26}\) However, another of his innovations on the standard multiple arch dam—the use of arches with curved upstream faces—did find expression in two completed projects (Cave Creek and Anyox) and helped to minimise concrete quantities (Figures 6 and 7). Before his death, Eastwood never publicly described how he discerned that a curved face design was more materially conservant, but in the 1930s confirmation appeared in the technical press.\(^{27}\)

5. ECONOMY

Although Eastwood’s dams primarily were financed by private interests, they were decidedly public structures in providing for development of the arid West’s scarce water resources. Eastwood constantly sought to maximise the financial efficacy of his dams and for him, his work found its greatest meaning within a competitive economic environment. In a 1913 letter published in *Engineering News* he disparaged the trend to increase the thickness of gravity dams in order to counteract the effect of ‘uplift,’ observing that: ‘Only by the use of a wide base can there be safety in a gravity dam and a wide base means a big bond issue.’\(^{28}\) To Eastwood, a ‘big bond issue’ dictated by the cost of a massive gravity dam design represented a waste of society’s economic resources and this perspective accords closely with how Billington allies structural art—and its attribute of reducing construction expenditures—with a greater social purpose. As Eastwood phrased it: ‘the cost of storing water is of special interest to the people of this state [California] and when this can be accomplished with equal or greater safety and at much less cost... they should not be deprived of these benefits.’\(^{29}\)

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From Hume Lake Dam, which undercut the cost estimate for the
original rockfill design by 37% (46 000 against 74 000), through the 53 m high, 220 m long Littlerock Dam (completed in 1924 for 430 000) where the California State engineer acknowledged that a multiple arch design was the only one economically feasible to build, Eastwood focused on developing the least expensive dams possible. His design for the Big Meadows Dam (1912) was to be approximately $500 000 cheaper than a gravity dam (estimated to be over a million dollars) and his Mountain Dell Dam, which openly competed with a flat slab buttress and a gravity design, undercut them both by more than 35%. In both of these instances the dam sites were accessible to railroad lines or other transportation facilities, belying the notion that multiple arch dams were only economically advantageous for remote locations.

Economic factors motivated Eastwood to innovate with the standard multiple arch form and develop ‘triple arch’ and ‘multiple cone’ designs that could reduce concrete unit costs. His early dams required small quantities of concrete, but their formwork also required detailed carpentry (Figure 8). To reduce expenses, he sought to exploit the economic advantages of casting mass concrete and in the early 1920s developed designs such as the Webber Creek Dam (built) and the San Elijo Dam (proposed) that utilised three or four wide-span arches. These designs—suitable for relatively narrow gorges—required concrete quantities comparable with more standard type of multiple arch dams but lessened the expense of erecting formwork and casting concrete.

6. ELEGANCE

With Eastwood’s dams, an observer confronts forms bearing scant resemblance to the bridges and long span vaults constituting the most prominent examples of structural art. Except for the ‘aesthetic of mass’ associated with monumental gravity dams (and the allied visual appearance of single arch dams), little precedent exists for viewing dams within an artistic context. However, once observers become familiar with multiple arch technology, the form can appear quite elegant and visually expressive.

Eastwood’s interest in reinforced concrete dams did not originate as a means of artistic expression, instead developing out of a utilitarian desire to impound large reservoirs at minimal expense. But despite a design orientation that would seemingly place little value on aesthetics, he clearly cared about the appearance of his dams. For example, consider the strut-tie beams used to provide lateral bracing for the buttresses at Big Bear Valley Dam (Figure 11). Constructed in 1910–11, these strut-tie beams consist of wonderfully expressive open-spandrel arches. Nothing requires the bracing to be so graceful in its form.

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form, but at the same time the materially efficient arch design is devoid of architectural adornment or embellishment. The strut-tie beams were conceived for the practical purpose of resisting seismic tremors, but beyond this, they imbue the design with an engaging flair. Later designs such as Murray Dam (1918), Lake Hodges Dam (1918) and Anyox Dam in British Columbia (1923) featured open spandrel arch strut-tie beam designs, affirming his commitment to the form (Figure 12).

This commitment did not occur in a professional vacuum, but instead was articulated in the face of strong opposition. These feelings are evident in a 1924 letter where he celebrated Anyox Dam’s performance in withstanding an overtopping through an uncompleted arch (Figure 13). Boasting of it being the ‘most beautiful dam in the world’ he further described Anyox as ‘one of the 17 strongest ‘Lace Curtain’ dams in the world,’ an allusion to the visual effect produced by the strut-tie beams extending between the buttresses.\(^3\) On the surface, this ‘lace curtain’ reference might seem a bit odd, but in fact it possesses deeper significance and relates to how others used visual/aesthetic criteria to oppose multiple arch dams.

First use of the phrase ‘lace curtain’ to describe an Eastwood design appears in a 1912 letter written by the prominent hydraulic engineer John R. Freeman to Arthur P. Davis, chief
engineer of the US Reclamation Service, concerning Eastwood’s Big Meadows hydroelectric dam then under construction. An influential proponent of massive gravity dams (at the time he was involved with construction of New York City’s Ashokan Dam) Freeman exhibited a strong distaste for Eastwood’s multiple arch design and its visual appearance (Figure 14). Pulling no punches, Freeman advised Davis that for Big Meadows he had ‘repeatedly informally urged’ the power company instead ‘to build a big massive lump of a dam.’ Significantly, Freeman’s arguments concerning the suitability of Eastwood’s design ultimately did not focus on technical issues so much as they did on matters of ‘psychology,’ visual appearance, and supposed public sentiment. For example, in his letter to Davis, he asserted that ‘the psychology of these airy arches and the lace curtain affects of [Eastwood’s] stiffening props is not well suited to inspire public confidence.’ Later Freeman recommended that the company fill in the downstream side of Eastwood’s dam with earth in order ‘to lessen the apparent height of the buttresses’ should this become desirable for ‘diplomatic or psychological reasons.’ And in a final report to the power company Freeman counselled that:

It is worthy of some considerable expenditure beyond that to satisfy engineers… in order to satisfy the more or less ignorant public… [who will] regard the dam not from a technical standpoint, but by comparison with the familiar type of solid gravity dam.

Here, the battle lines were drawn and the visual elegance of the multiple arch dam—in contrast to the big massive lump of an architecturally adorned gravity design—was brought to the fore in arguments (made by a professionally prominent engineer) seeking to block its adoption (Figure 15).

The fullness of the Big Meadows controversy is beyond the scope of this article, but Eastwood considered Freeman’s efforts to alter the appearance of his dam to be ‘idiotic’ and he saw no value in gerrymandering the design in response to nebulosity ideas about ‘psychology’ or what the public (as guided by Freeman) might expect a dam to look like. On this issue Eastwood’s resolve never wavered and he never attempted to compromise the appearance of his designs as a means of making them more palatable or acceptable to critics.

7. ‘ALL LINES ARE CURVES…’

In confronting the myriad problems associated with economically efficient dam design Eastwood believed that his methodological approach was based upon ‘true scientific principles.’ But as part of this, he rejected the notion that ever more complicated mathematical analysis would inevitably foster better design or that a scientific approach to design required a slavish adherence to mathematical formula. Because the use of mathematical theory by engineers is often portrayed as one of the great fruits of the melding of science and technology, it is worth noting how Eastwood used such theory in designing multiple arch dams. In this example, discussion focuses on the elastic theory of arches that received much attention in the early 20th century and was often perceived as a major advancement in engineering analysis.

While cognisant of elastic theory, Eastwood eventually became skeptical of its value, opting instead to rely upon the simpler ‘cylinder formula’ \( T = P \times R/Q \) for dimensioning his arch designs (formulated by Navier in 1826, in this formula \( T \) equals arch thickness, \( P \) is water pressure, \( R \) is arch radius and \( Q \) is allowable stress). The cylinder formula neglects any consideration of an arch’s tendency to compress or deform under loading and, in contrast to elastic arch analysis, makes no attempt to account for stresses induced by temperature change or by ‘rib-shortening.’ Thus, on first glance, use of the cylinder formula would appear to be less ‘scientific’ than use of the more sophisticated elastic theory. Aware of elastic arch theory as early as 1912, Eastwood used it to analyse arch stresses in his Big Meadows design. He subsequently took rib-shortening/temperature stresses very seriously and his first designs after Big Meadows featured arches encompassing very deeps arcs (elastic theory indicates that rib-shortening stresses are at a minimum when an arch encompasses 180 degrees and increase as an arch flattens out). Even more significantly, for Kennedy Dam (built 1914) and Mountain Dell Dam (built to 33 m height in 1916–17) he went so far as to employ three-hinge arches capable of rotating and adjusting to rib-shortening/temperature stresses (Figure 16).
Ironically, he notes that the United States, one of the leading structural engineers in the world, was one of the few countries that did not develop a strong tradition of structural art. Freeman—that held great influence in 20th century America—exemplified by his nemesis John Eastwood who perceived in Freeman a desire to be ‘a gentleman, a professional, an artist, a leader.’ Freeman writes, ‘I was always a business man, an engineer, and a professional man… I was not a gentleman of the arts.’

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8. CONCLUSION

Eastwood stands as a major figure in the history of structural design and no other native-born American practitioner in reinforced concrete better exemplifies the ideals of structural art. The question then arises as to why he has largely languished in obscurity since his death. One reason for this is that his practical approach to design and his scepticism about ever more complicated mathematical theory ran counter to professional trends in 20th century dam design. But perhaps even more important is his separation from the business-oriented civil engineering fraternity—exemplified by his nemesis John Freeman—that held great influence in 20th century America.

In The Tower and the Bridge, Billington associates massive masonry design with the ‘preindustrial imperial era’ while projecting structural art as exhibiting ‘a lightness, even a fragility, which closely parallels the essence of a free and open society.’ Ironically, he notes that the United States, one of history’s most prominent democracies, suffers from a ‘relative lack of structural artists,’ a phenomenon attributable to American engineers perceiving themselves as ‘servants of business.’ Strong words to be sure, but ones that resonate with Freeman’s opposition to Eastwood’s efforts in promoting the multiple arch dam.

Freeman was a long-time leader in the factory insurance industry and his alignment with America’s business community has been affirmed by historian of technology Bruce Sinclair, who perceived in Freeman a desire to be ‘a gentleman,
comfortable in the boardroom, a man who might also be elected a director of the firm. Combining this with his professional prominence as president of both the ASCE (1922) and the ASME (1905) and his role in planning major water supply systems for Boston, New York City, and San Francisco, Freeman's opposition to the multiple arch dam represented a formidable barrier. As A. G. Wishon, Eastwood's colleague and the Fresno-based general manager of the San Joaquin Light and Power Corporation bemoaned to him in 1922: 'the prominence of John R. Freeman in the engineering world and his influence with men of capital has delayed the storing of water ten to fifteen years.' Even after his death in 1932, Freeman's legacy held strong and when the history of dam engineering was celebrated at the 100th anniversary of the ASCE in 1952, multiple arch dams received scant attention and Eastwood no mention at all.

For men such as Freeman and others who embraced massive gravity dam technology, the design of new structural forms for water storage held little allure. Eastwood, an engineer from the hinterlands of California who never fit into the boardrooms where so many business-related engineering decisions were made, struggled to procure commissions, finding success only when the objections of Freeman and fellow travellers could be avoided or overcome. In the end, the dams themselves, built largely for enterprises with limited access to capital, became for Eastwood the ultimate means of accomplishment. His pride in the multiple arch dam is undeniable and a joyous, self-conscious desire for achievement—and its related affirmation that critics such as Freeman were wrong—is central to his work. In a letter written shortly before his death, he extolled the satisfaction that came with construction of Anyox Dam:

My joy in life is in doing each one a bit better than the one just completed. At Anyox I had no ‘critics’ and built it as it should be, and was able, by reason of my getting a ‘free hand’ to give my clients...the best service and the most complete dam in every particular in the world.

As Billington describes all structural artists: ‘At the heart of the technology they found their own originality, they created personal styles without denying any of the rigor of engineering.’ This was certainly the case with Eastwood, as he explored—and revelled in—his own distinctive vision of the possibilities offered by concrete in the development of water storage structures. But, in terms of dams and structural art, Eastwood certainly does not need to stand as sui generis. In this light, the author encourages researchers to carry out investigations into other innovative dam designers such as Lars Jorgensen, Fred Noetzli, B. F. Jakobsen, and Andre Coyne (to name but a few) to analyse how their work accords with the ideals of structural art promulgated by Billington. Eastwood's name but a few) to analyse how their work accords with the ideals of structural art promulgated by Billington. Eastwood's work in dam design may have been dauntingly innovative, but there is no reason to believe that he represents the only practitioner through which the analytic prism of structural art can help enhance our understanding of hydraulic engineering history.

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