SESSION 8. NON–STRUCTURAL APPLICATIONS

Session Chairman

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STRUCTURAL ANALYSIS AND THE HUMANITIES

by

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The contemporary challenge that engineers should become more sensitive to the effects of their technological decisions is in essence an exhortation to assimilate the cultural values implicit in "historic insight and social memory." A Princeton University program is described which responds to this challenge by introducing engineers to their own humanistic tradition. To illustrate how matrix analysis of structures can be taught in a humanistic context and can be applied to humanistic research, five case studies from the Princeton program are discussed. These include: the analysis of Eiffel's Maria Pia Bridge, a design study of Revell's Toronto City Hall, research of the structural performance of the ribbed vaults of Gothic cathedrals, the analysis of a Maillart concrete plane frame, and a critical study of Saarinen's Kresge Auditorium.

Humanistic Studies in Engineering

Matrix analysis of structures is being increasingly applied to humanistic studies at Princeton University. These endeavors are part of an overall educational program which is responding to the pervasive concern in American society regarding the role of technology in modern culture. The purposes of this paper are to describe briefly the Humanistic Studies in Engineering program and to discuss some of the projects from this program which entail the matrix analysis of structures.

Humanism and Engineering Technology

Much has been said in the last few years about the effects of technology on society. Engineers are certainly conscious of the criticisms levied against their profession for the failings and ill effects of engineering technology: the deterioration of the environment; the dehumanization resulting from computerization and automation; the apparent inability of public works engineering to ameliorate the blight of urbanization; and the unconscionable development of frightening and

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expensive weapons systems. On the other hand, the engineering profession has made acknowledged contributions to the positive aspects of the prevalent western life style, a style based upon a high standard of living with its familiar technological underpinnings: industrialization, mobility, public health services, modern utilities, etc. This superficial listing of some favorable and unfavorable effects of technology on society neglects the complex technical-political-economic interactions that characterize societal processes. Nevertheless, it is clear both that engineering technology is a major influence in modern culture and that cultural values are invoked in the discussion of technology and society.

One might define humanism as a concern with cultural values, with the "expressive, moral and contemplative aspects of living"(1)*. Thus when Lewis Mumford criticizes engineers for lacking "historic insight and social memory" in conceiving and executing projects, he is accusing the profession of a lack of humanism. This is the essence of the contemporary challenge that engineers should become ever more sensitive to the widespread effects of their technological decisions. Of course, the development of a closer relationship between technology and the humanities presents a challenge to humanists as well. They must recognize and explore the new possibilities created by technology, the "new attitudes and perceptions, new belief systems, and new ways of looking at the world."(1) To meet the goal of a closer relationship between engineering and the humanities, an experimental program in engineering education has been initiated at Princeton.

The Princeton Program(2)

The first objective of the Humanistic Studies in Engineering program is to educate engineers who, while fully competent in engineering science and design, will center their careers on a union of technology and the humanities. The principal focus here is on introducing engineers to their own humanistic tradition through a modified engineering curriculum as well as through the usual approach of elective courses in the humanities. To include humanistic considerations in their own teaching, the engineering faculty involved in the program have been studying in the humanities. In addition, humanistic scholars such as art and architectural historians have been increasingly involved in the program through collaboration with the engineering faculty and through the broadening of their own interests and course content to include aspects related to engineering.

In striving to achieve a closer relationship between engineering and the humanities, the program must develop a communication that is mutually stimulating. Therefore, the second major objective is to establish a tradition of engineering research directed toward new

*Numbers in parentheses indicate references listed at the end of this paper.

humanistic understanding. Significant research will encourage the involvement and collaboration of humanists in engineering education. So far, the research efforts at Princeton have centered on the history of architecture and the related arts. Throughout the research aspects of the program, a consistent effort is made to maintain a strong technical component that is absent from the research of traditional humanists. For instance, quantitative structural analysis has proven to be a decisive tool in the study of Gothic architecture.

The program is being implemented in several ways. In the classroom a humanistic emphasis has been incorporated into the context of several civil engineering courses by discussing applications and examples which have cultural and historical as well as technical significance such as James Eads' St. Louis Bridge. Undergraduate students are encouraged to undertake course projects and independent work which further explore, for example, the relationship between engineering and aesthetics. Research efforts involving graduate students and faculty in the humanities as well as in engineering are another aspect of the implementation; these efforts concentrate on history, biography, the relation between engineering and aesthetics, and the evaluation of contemporary engineering works. A natural adjunct of this research is the accumulation of documents and other source material related to humanistic studies in engineering. Publication of the research is an important element of the program; additional types of publications planned are engineering textbooks written in the context of the humanities and critical essays regarding specific engineering and architectural projects. Faculty and student interaction is furthered by periodic colloquia on humanistic research related to engineering and on value judgments encountered in engineering practice such as in the development of low-cost urban housing. Finally, to broaden the impact of the program and to stimulate similar undertakings elsewhere, public lectures are given at various campuses and other locations, research fellows from other institutions are brought to Princeton, and a national conference ("Civil Engineering: History, Heritage and the Humanities") has been held.

Structural Engineering and the Humanities

The Humanistic Studies in Engineering program is presently based in the civil engineering department. Moreover, it strongly emphasizes structural engineering, largely because a major stimulus for the development of the program was the interaction between engineering faculty and architecture students in structures courses. The interests that these students initially expressed are reflected in the nature of the current program studies: the analysis of the structures of architects such as Antonio Gaudi and Eero Saarinen, the study of the life and works of the great engineer-builders such as Pier Luigi Nervi and Eduardo Torroja, and the analysis of other structures significant in the history and theory of architecture such as Gothic cathedrals. Corresponding to the close relationship between structures, architecture, and the visual arts, the humanists from the Princeton faculty who are most actively involved in the program at present are architects and art historians.

The intermediate level courses in structural analysis and design have been broadened to include a humanistic perspective, and thus they serve as examples of the implementation of the program in the classroom. In addition to the customary rigorous consideration of engineering science and design, two emphases are present in these courses. The first is the consideration of the origins of modern structures and practice(3). The humanistic tradition in modern structural engineering is firmly rooted in the careers of the great builders of the late 19th and early 20th centuries, men like John Roebling, James Eads, Gustave Eiffel, and Robert Maillart. The discussion of the ideals and accomplishments of these men serves a dual purpose: not only do their works have a definite influence on modern architecture and art, but the technical aspects of their structures also provide worthy examples for the study of structural theory and design. The second humanistic emphasis in structures courses is the criticism of contemporary buildings. Qualitative and quantitative analyses of both outstanding and ordinary structures permit the student to develop an ability to relate visual elegance to structural efficiency.

Humanistic research in structural engineering is a natural extension of the classroom emphases, that is, the three main elements are history, biography, and criticism. Several topics are worth mentioning to illustrate the current thrust of research. Studies of Eads' St. Louis Bridge and Roebling's Brooklyn Bridge highlight the cultural and historical significance of these structures. Not only are the structures themselves symbols of the city and the era that produced them, but the historical investigations are enlightening introductions to 19th century politics. Moreover, both bridges have had an impact on the visual arts, especially the Brooklyn Bridge which is profusely represented, for example, in the paintings of Joseph Stella and the etchings of John Marin. Another research topic is a biographical study of Robert Maillart. This effort is still in an early stage wherein source documents and interviews are being obtained from Maillart's family and colleagues. An example of criticism is an examination of some of the buildings of Sir Owen Williams, a civil engineer turned architect. Finally, an investigation of the relation between engineering and aesthetics is a joint study by engineers and a social scientist of the design competition for the Washington Bridge over the Harlem River and of the planning decisions involved in subsequent changes in the urban area adjacent to the bridge.

Model studies are the primary structural analysis method in many of the projects that have already been mentioned. However, computer techniques are being increasingly applied to humanistic research, both alone and as a complement to model studies. In the remainder of this paper various case studies that utilize matrix methods of structural analysis will be discussed in further detail.

Case Studies Involving Matrix Analysis

The work reported here involves no original contributions to the technology of matrix analysis with one exception (4) which will be published in detail elsewhere. The purposes, therefore, of recounting these investigations are first to demonstrate how the matrix analysis of structures can be studied in a humanistic context and second to indicate a range of humanistic structural research to which the powerful tool of computer analysis can be applied. Consequently, in the discussions which follow emphasis will be placed upon the description of the problems and their significance rather than upon detailed quantitative results.

Eiffel's Maria Pia Bridge

The work of Gustave Eiffel has had a profound effect not only upon the practice of engineering, but also upon architecture and art.(3) His technical contributions included advances both in the design, fabrication and erection of metal structures and in the analysis and design for wind loadings. Developments in these areas can be traced in the series of iron railroad viaducts designed and constructed by Eiffel and his associates from 1864 to 1886. The culimination of Eiffel's structural work, the tower bearing his name, is a classic of metal construction. Its form is an eloquent expression of proper design of a tall structure to resist wind loading. This engineering work has become the best known symbol of France. Further evidence of the cultural significance of Eiffel's work is the fact that such influential observers as LeCorbusier(5) and S. Giedion(6) prominantly feature his viaducts and tower in their treatises on architecture.

A study project on Eiffel, presently concentrating on one of the Eiffel viaducts, the Maria Pia Bridge across the Douro River at Oporto, Portugal, is providing an opportunity for engineering learning experiences in a humanistic context. The bridge, designed and construced during 1875 to 1878, was the first two-hinged arch executed by Eiffel and with a span of 160 meters (525 feet) was the longest metal arch constructed up to that time. (See Figures 1 and 2.) An erection scheme was devised wherein the arch was erected without scaffolding from the springings upward; the two rising segments of the arch were suspended from the side-span superstructure by steel cables as successive prefabricated sections were lifted from barges. The overall design and erection was nearly 50% cheaper than its nearest competitor in the bidding. Historically, this structure marks the development of many of the new ideas that were later incorporated on a grander scale into Eiffel's most famous bridge, the Garabit Viaduct. Like the Garabit, the Maria Pia elegantly expresses its efficient structural function(3). For example, in plan the wider spacing of the legs of the arch at the support reflect the resistance to lateral overturning by wind forces.

FIGURE 1. EIFFEL'S MARIA PIA BRIDGE ACROSS THE DOURO RIVER, OPORTO, PORTUGAL (from The Engineer, Vol. 45, 1878)

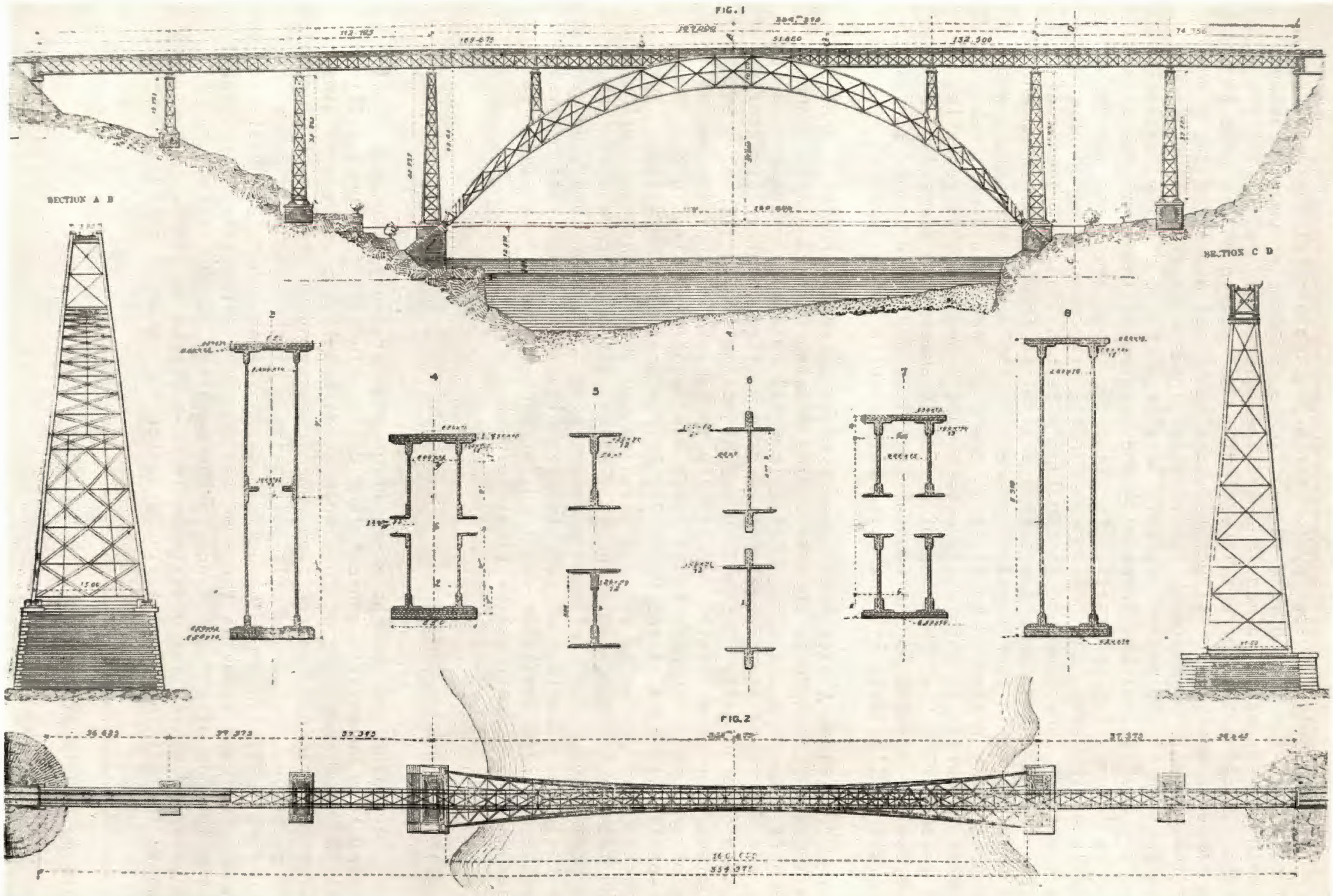

FIGURE 2. ELEVATION, DETAILS AND PLAN OF MARIA PIA BRIDGE (from The Engineer, Vol. 45,1878)

Fortunately, a paper by T. Seyrig(7), the project engineer from Eiffel's firm for the Douro bridge, gives a reasonably complete account of both the structural dimensions and the structural analysis of the bridge. Because the current investigator was seeking an exercise in the computer analysis of structures, the technical aspect of the study was the analysis of the arch for vertical loads with ICES-STRUDL II and a comparison of the modern analysis results with the original analysis. Seyrig's analysis of the internally and externally indeterminate trussed arch is interesting in itself. By using the gross areas and moments of inertia of the arch, the horizontal thrusts are computed by an approximate method* analogous to Castigliano's Second Theorem. The axial forces in the chord members are then determined from the gross moment and axial force in each panel. Apparently, the web member forces are conservatively estimated by first omitting one set of diagonal web members to obtain an internally determinate truss and then repeating the process with the other set of diagonals absent. A comparison of some typical results for horizontal reactions and chord member stresses is presented in Table 1; the agreement is quite good.

Many student exercises undertaken in current structural analysis courses are portrayed as anonymous line drawings or are simple example drawn from current practice. A supplemental purpose of studies such as the one described is to develop student exercises based on structures which are technically outstanding and historically significant. Such problems provide a natural opportunity to explore further the aesthetic and other humanistic aspects of these and associated structures. In the particular case of the Maria Pia Bridge analysis, additional opportunities accrue to the student. He can observe the application of hand methods of approximate analysis which, although now out of fashion, are still useful for preliminary analysis. On the other hand, he can see the clear advantage of computer techniques for a complete analysis when he observes the labor required for hand analysis for, say, wind loadings and assymetrical vertical loads.

Revell's Toronto City Hall

A senior thesis that exemplifies undergraduate structural engineering in a humanistic context is a design study of the Toronto City Hall(8). One component of this work is an examination of the origins, design competition, construction, and functioning of the municipal complex. This treatment includes a critical analysis of the aesthetic appeal and structural efficiency of the buildings. A second, more technical component of the study is the exploration of an alternative structural scheme for one of the buildings in the complex. Enough structural analysis and design was undertaken in this aspect to provide the student with an insight into engineering practice for concrete buildings.

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*This method is attributed to deDion(7).

TABLE 1. COMPARISONS OF ANALYSES OF MARIA PIA BRIDGE

	Panel Number	Top or Bottom Chord	Loading 1		Loading 2		Loading 3	
			STRUDL 2	Seyrig	STRUDL 2	Seyrig	STRUDL 2	Seyrig
Horizontal Reaction, kg			140,950	140,310	95,770	95,000	70,570	70,150
Member stresses, kg/mm^2	3	top	-1.25	-1.08	0.53	0.20	-2.09	-2.20
	3	bottom	-2.06	-1.85	-2.00	-1.96	0.01	0.32
	5	top	-1.64	-1.60	-0.22	-0.16	-2.46	-2.63
	5	bottom	-1.47	-1.32	-1.84	-1.81	0.74	0.94
	7	top	-1.45	-1.40	-0.88	-0.89	-2.23	-2.23
	7	bottom	-1.61	-1.41	-1.31	-1.22	0.51	0.69
	9	top	-1.86	-1.92	-1.90	-1.94	-2.01	-2.07
	9	bottom	-0.90	-0.71	-0.04	0.09	0.69	0.84
	11	top	-1.89	-1.89	-2.10	-2.16	-0.95	-0.95
	11	bottom	-0.69	-0.51	0.34	0.62	-0.35	-0.25

Notes: Panels are numbered consecutively from the hinge. The top center panel is number 11. See Figure 2.

All loadings represent distributed loadings of intensity 4000 kg/m.
Loading 1 is a symmetrical loading of the full 160-meter arch span.
Loading 2 is a symmetrical loading of 80 meters in length.
Loading 3 is an asymmetrical loading of 80 meters in length of the half arch span. For loading 3 the stresses shown are for the members beneath the load.

In 1957 the city of Toronto launched a worldwide architectural design competition for a city hall and civic square. The city was seeking a building that would be a dramatic symbol of Toronto, a symbol of achievement and promise. The plaza accompanying the building was to be designed for the pleasure of the urban residents. From among 520 entries in the first stage of the competition, eight finalist were chosen to submit more detailed designs. Ultimately, the unanimous decision of the jury was that the design submitted by the Finnish architect Viljo Revell was the most original and that it should be implemented (Figure 3). However, the jurors were not without reservations regarding the design. There was no doubt that the strikingly curved buildings would remain a prominent feature on the Toronto skyline regardless of other buildings that might surround it in the future. Nevertheless, a minority of the jurors were disturbed that the windowless outer wall turned a blank face on the urban redevelopment area to the north. This lack of windows on one wall is also a potential shortcoming from the standpoint of internal space utilization.

The structural concept of the curved towers is of particular concern here. To avoid interior columns, Revell had envisioned the outer walls as curved shells from which the floors would be cantilevered. The jury's reaction to this scheme was that the omission of columns would unnecessarily add to the cost of the building without significantly altering the visual effect. Oddly, despite the jury's recommendations, the original structural design proceeded without columns; however, this approach was abandoned when the shell thickness reached 32 inches and still was inadequate to support the cantilevered floors(8). Radial beams and a row of columns along the midline of the buildings were added. Nevertheless, the overall towers were designed as vertical cylindrical shells made orthotropic by the horizontal floor slabs and a system of reinforcing columns(9). As built, the outer wall of the east tower is an 18-inch thick concrete monolith, horizontally and vertically reinforced.

Stimulated by reservations about the windowless wall and about the structural rationale of the shell, the student decided to investigate a structural scheme that might permit a greater architectural flexibility. If the towers were designed as frames, the shell wall could be partially or totally omitted. No changes in the basic floor plans were considered in order to limit the scope of the work so that one man could reasonably accomplish the study. The taller east tower was chosen. An initial design based on the existing framing dimensions was selected: radial beams, columns along the outer wall, and interior columns were already present, while tangential beams were added to complete the framing. ICES-STRUDL II was employed to analyze selected vertical and horizontal segments of this three-dimensional frame for dead, live, and wind loadings. It was found that by current code standards, concrete framing with the existing cross sections could be adequately reinforced to satisfy the necessary strength requirements. Although no new design for the outer facade was specifically proposed, the results of the structural study demonstrated new aesthetic potentialities.

 

FIGURE 3. FRONT AND BACK VIEWS OF REVELL'S TORONTO CITY HALL

Gothic Cathedrals

One of the major influences on architecture and art has been the Gothic cathedral. These buildings have a manifest historical and cultural significance but in addition they have played a key role in the formulation of the architectural theory of rationalism(10). This theory was succinctly stated by Louis Sullivan as "form follows function." The first modern Gothic scholar, Eugène Viollet-le-Duc, laid the foundations for the rationalist theory in studies associated with his work of preserving and restoring the French Gothic cathedrals. He abstracted the theory from his contention that every element of the Gothic cathedral had a structural function(11), and he soon acquired a following among contemporary architects such as Sullivan. More recent inheritors of the rationalist tradition include Antonio Gaudi, Frank Lloyd Wright, and Mies Van der Rohe and engineers like Maillart, Torroja, and Nervi. The rationalist theory is more completely delineated in References 3, 4, and 10.

Counter to the rationalist school of thought are those who believe that architectural form is derived from purely aesthetic intentions.* Most of the debate on these opposing theories that has occurred since Viollet-le-Duc's time has involved structural theory but has consisted essentially of qualitative arguments set forth by architects and historians. There is a clear opportunity for modern structural analysts to contribute to the settlement of some of these controversies. Hence, a continuing line of faculty and graduate research at Princeton has been studies of the theory of rationalism.

Although the theory of rationalism is not specifically tied to Gothic architecture, many of the particular structural questions under debate by the theorists involve the Gothic simply because the influential Viollet-le-Duc drew most of his examples from his own broad experience with Gothic cathedrals. In Figure 4, two sectional views of the nave of Amiens Cathedral are shown. Although dimensions vary from church to church, essentially the same structural elements are present in other Gothic cathedrals. Most of the arguments about the rationality of Gothic construction are concerned with the vault and buttressing systems. In particular, the elements whose structural functions have been most disputed are the vault ribs, the flying buttresses, the outer buttress, and the pinnacles.† Numerical structural analysis in progress at

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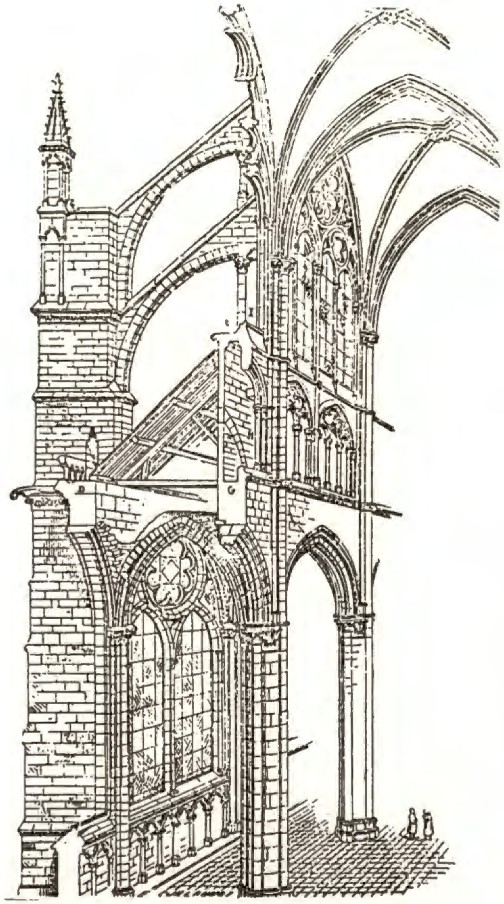
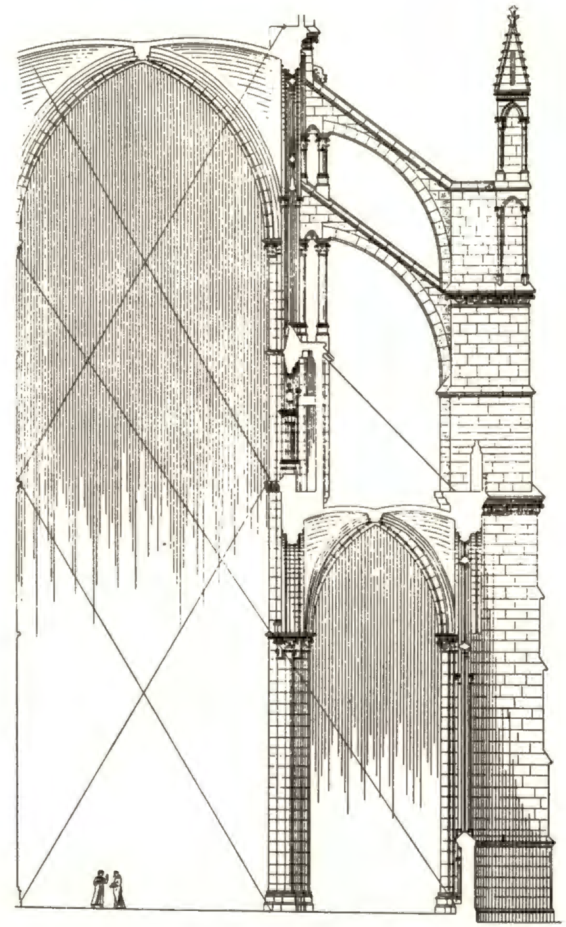
*As evidenced by their buildings, modern architects who are decidedly non-rationalist include Eero Saarinen and Jørn Utzon.

†Photoelastic model studies at Princeton have indicated that the pinnacle must be present and must be located as shown in Figure 4 in order to overcome tensions in the outer buttress of Amiens Cathedral.



(a) From Viollet-le-Duc



(b) From Dehio and Bezold, Die Kirchliche Baukunst des Abendlandes

FIGURE 4. NAVE SECTIONS OF AMIENS CATHEDRAL

Princeton are concerned with two aspects of the behavior of the ribbed vaults. The first project is to compute the horizontal thrusts developed by the vaulting system; these must be known in order to evaluate fully the role of the buttress system. The second study is to investigate the structural function of the ribs.

The geometry of the vault shells is quite complex. Figure 5 shows a model of two nave-vault bays of Cologne, a cathedral for which relatively complete geometric data is available. Note the double curvature of the shells, particularly along the nave-axis crown. The finite element method is being used for the numerical studies. In addition to the complex geometry, the difficult points in the analysis are the diagonal groins, the out-of-surface boundary conditions at the crown, and the introduction of the ribs. Dr. Sachs has developed a double curved shell element that accomodates the groin and the necessary boundary conditions, and he has computed the thrust(4). Further analyses are utilizing quadrilateral element assemblages of planar triangles(12). Preliminary numerical results are being verified by comparison with photoelastic model studies of the vault model shown in Figure 5. Because the project is still incomplete, it is too early to present any conclusions about the structural action of the ribs. Nevertheless, this research effort is an example of how matrix analysis of structures can contribute to architectural history scholarship.

A Concrete Frame by Maillart

An independent-study project recently undertaken by an undergraduate was the analysis of a concrete plane frame by two methods, matrix analysis and photoelastic modelling. The frame is a rather unusual one designed by Robert Maillart. The technical phase of the study enabled the student to learn more about the two methods of analysis by comparing their results. The nontechnical aspect was a critical study of the structure as it related to other work by Maillart. Hence, the general approach of this project is similar to that of the Maria Pia project discussed earlier.

Maillart (1872-1940) was a Swiss engineer-builder who, although less well-known and less influential than Eiffel, has made a considerable contribution to both engineering and the arts. In contrast to Eiffel's concentration on metal structures, Maillart was an early master in reinforced concrete construction. His arch bridges are concrete manifestations of rationalist design and visual elegance(6). Maillart's cultural impact is epitomized by a distinction few engineers receive: a sculptor, Max Bill, has assembled an architectural book entirely devoted to Maillart(13). In addition to a variety of examples of rational design, Maillart's technical contributions include the development of flat-slab floor construction with mushroom columns, the testing of large-scale concrete structures, the origination of the concept of the "shear center", and the advocacy of a theory of design for uniform safety in concrete structures(14).

FIGURE 5. MODEL OF COLOGNE CATHEDRAL NAVE VAULTS

FIGURE 6. MAILLART'S SHED ADJACENT TO MAGAZZINI GENERALI, CHIASSO, SWITZERLAND

The Maillart frame selected for this study is a typical bay of the shed adjacent to the warehouse Magazzini Generali in Chiasso, Switzerland, Figure 6. This frame has been admired for its airy, plant-like form but also has been criticized as affecting a form too technical to be intuitively grasped(13). An elevation of half of the frame is shown in Figure 7. From this an engineer can certainly see that the form follows the function. The "truss" region with parabolic profile between the columns corresponds to an inverted moment diagram for a uniformly loaded beam; hence the chord members should tend to have little bending and equalized axial forces. Table 2 gives some results of both an ICES-STRUDL II analysis and the photoelastic model analysis. In general, both analyses confirm the functional interpretation of the form.

However, the two analyses do not agree very well for many of the individual members; it is in understanding this disagreement that much of the technical educational value of the analysis lies. Many of the members are not slender enough to enable the idealized frame to fulfill the assumptions inherent in the computerized frame analysis. On the other hand, although the photoelastic study is a full-field, two-dimensional analysis which accounts for complex behavior at the joints, it is not easy to obtain very accurate measurements of axial forces and bending moments in the members from the fringe photographs. (The forces and moments were chosen for comparison because they would be used in frame design.) Finally, it is valuable to contrast these linear elastic approaches with Maillart's ideas regarding design for uniform safety, ideas which implicitly call for an understanding of the real (cracked, nonlinear) behavior of the structure as a whole(14).

Saarinen's Kresge Auditorium

The modern implications of the theory of rationalism in architecture become evident in the critical analysis of contemporary structures. One such study undertaken at Princeton is of Eero Saarinen's Kresge Auditorium on the M.I.T. campus, Figure 8. This shell, completed in 1955, is exactly one-eighth of a sphere, supported at three points. The distance between abutments is 155 feet and the arched edges rise to 27 feet. Although the design was originally hailed by architectural critics as a rational solution, the structure has experienced enough structural shortcomings to indicate the contrary.

The first part of the study, the investigation of the particulars of the design, construction, and performance of the building, has historical significance because Kresge was one of the first large shell structures to be built in the United States. This part of the research was conducted by surveying the architectural and engineering literature and by interviewing individuals who were involved in the design and construction of the auditorium. A complete account of this study will be reported elsewhere; however, a few key findings are of interest here. For example, in the design stage, the engineers recognized the necessity of edge beams. Nevertheless, when the forms were removed from the shell, the edge deflections proved to be excessive, particularly with creep;

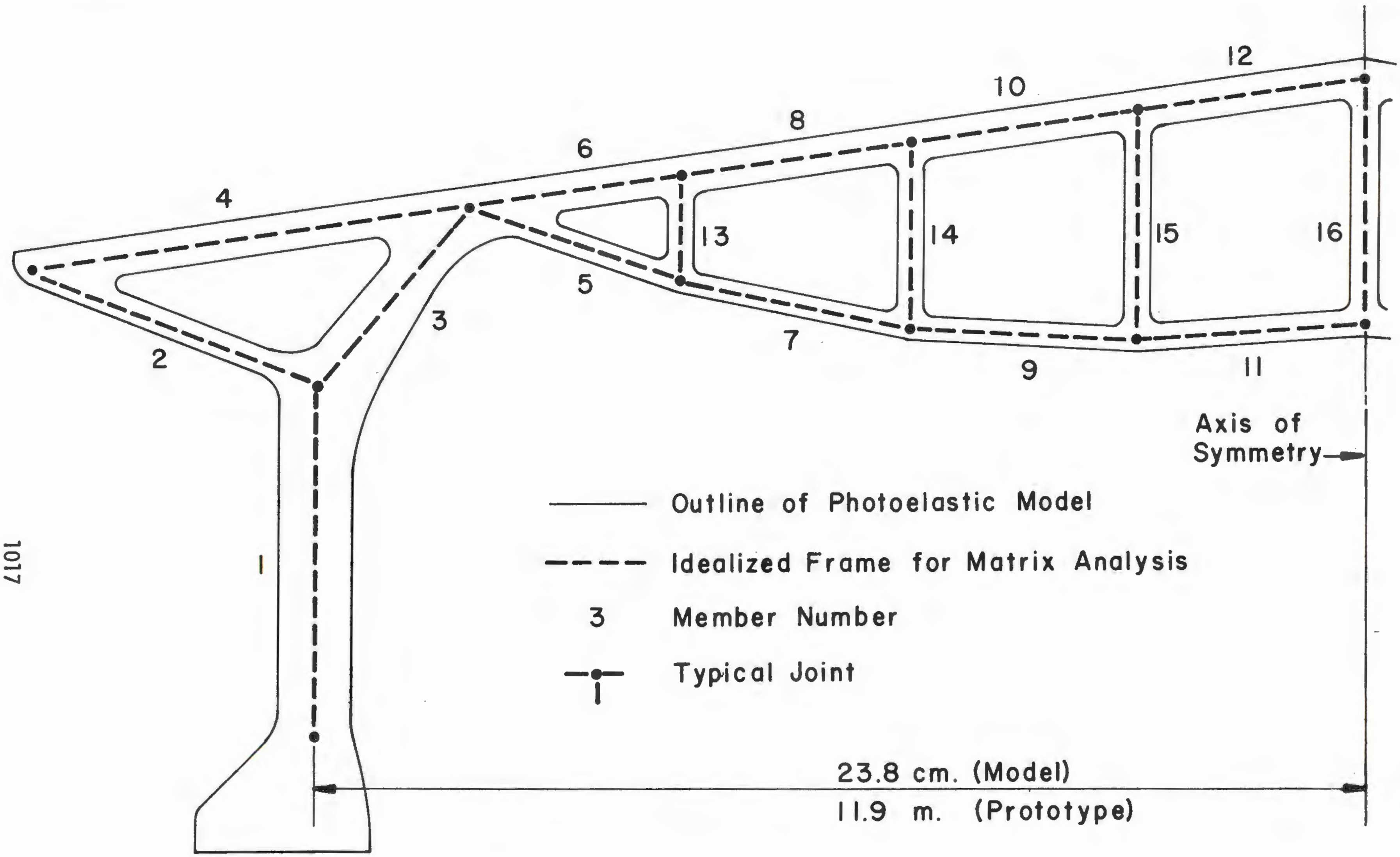


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FIGURE 7. ELEVATION OF MAGAZZINI GENERALI SHED FRAME

TABLE 2. COMPARISONS OF ANALYSES MAGAZZINI GENERALI SHED FRAME

Member Type	Member Number (Fig. 7)	Axial Force (kips)		Bending Moment (k-in)	
		STRUDL	Model	STRUDL	Model
Supporting Frame	1	-70	-69	750	1260
	2	-25	-24	16	21
	3	-73	-101	840	900
	4	+24	+18	75	160
Bottom Chord	7	+78	+88	24	21
	9	+78	+94	8	25
	11	+78	+88	7	12
Top Chord	8	-93	-113	98	150
	10	-96	-123	170	160
	12	-95	-102	150	150
Web Verticals	14	-12	-17	91	60
	15	-11	-21	17	5
	16	+12	+24	0	0

Notes: See Figure 7 for member numbers.

Loading is dead and snow loads only.

STRUDL analysis includes member end sizes and transverse shear deformation.

Bending moments compared are the highest quarter-point moments.

FIGURE 8. SAARINEN'S KRESGE AUDITORIUM, M. I. T.

FIGURE 9. CENTRE NATIONALE DES INDUSTRIES ET DES TECHNIQUES (CNIT), PARIS

and despite aesthetic objections by Saarinen, mullions were added to the window walls to support the edge. Despite these and other efforts to strengthen and support the shell, the performance of the structure has not been satisfactory. Cracking and leaking have occurred, especially near the abutments, and the flexing of the shell under varying thermal loads has necessitated the refurbishment of the roofing at a cost of at least $250,000(15).

The second phase of the investigation was a comparison of Kresge with other large, point-supported shell structures that were of similar concept and function. This comparison involved not only aesthetics but also a qualitative structural evaluation. One of the buildings considered was the Centre Nationale des Industries et des Techniques (CNIT) in Paris, Figure 9. Several architects and engineers participated in the design of this structure(16); Pier Luigi Nervi, Eugene Freyssinet, and Nicolas Esquillan were the well-known engineers who were successively involved. The CNIT consists of three intersecting cylindrical segments and, like Kresge, is supported at three points. However, the building is much larger than Kresge (675 feet between abutments, 152-foot rise) and for stability considerations is a double shell.

The final aspect of the study was a numerical structural analysis of Kresge to provide a more detailed focus on the deflection and stress problems at the edges. In addition, a structure of CNIT's configuration and Kresge's span was also analyzed for contrast. The finite element method was used(12). The analysis confirmed that only the central portion of Kresge acts truly as a shell; in essence, the central spherical dome is supported by the edge arches, and the in-surface and arch bending are responsible for the cracking and excessive deflection along the edges. Some of the numerical analysis results of Kresge and CNIT are qualitatively compared in Figure 10. The upward flow of forces in Kresge represent tensions arising from the in-surface bending behavior necessary to provide adequate support for the central portion of the dome, which acts as a membrane. In addition, the edge deflections of the Kresge-sized CNIT structure were found to be one and a half orders of magnitude less than those of Kresge without mullions.

This case study provides a modern example for architectural theorists. More significant, however, is the fact that it combines criticism, one of the main characteristics of the humanistic approach, with engineering. Since architectural design from purely aesthetic or decorative considerations may have unacceptable social, functional, and monetary costs, engineers must become critics and participate in non-technical value judgments.

Concluding Remarks

The Humanistic Studies in Engineering program, as exemplified by the five structural engineering studies discussed above, is designed to enhance engineering education and ultimately professional practice. A

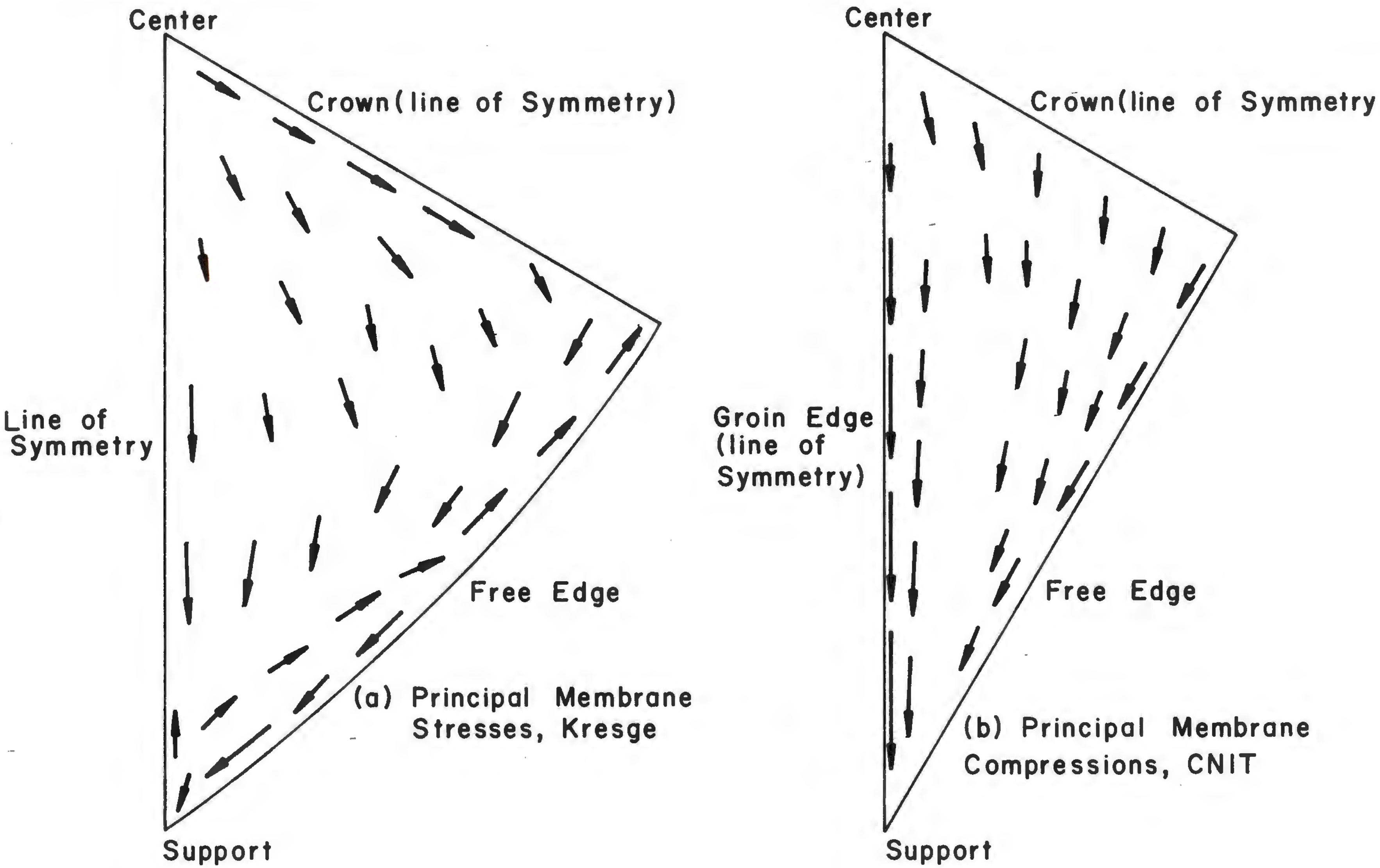

FIGURE 10. SCHEMATIC, PLAN-VIEW COMPARISON OF THE FLOW OF MAJOR PRINCIPAL MEMBRANE FORCES IN ONE-SIXTH SEGMENTS OF KRESGE AND CNIT SHELLS (after Reference 15)

humanistic emphasis which is now generally ignored in engineering courses and texts is being integrated into the curriculum. In addition structural engineering is contributing to research in the humanities, including criticism.

Acknowledgments

The author gratefully acknowledges the efforts of various students in the Department of Civil and Geological Engineering. John V. Santosuosso, Visiting Fellow, conducted the Maria Pia Bridge study. John Matheson '71 did the senior thesis on the Toronto City Hall. Dr. Klaus Sachs, Ph.D.'71, and Kevin O'Neill, graduate student, have contributed to the investigations of Gothic vaults. James K. Chiu '71 performed the study on the Maillart frame, H. R. Werner, Jr., '70, M.S.E. '71, did the critical analysis of Kresge Auditorium. The author is also indebted to his colleagues David P. Billington and Robert Mark for their advice in preparing this paper. The Princeton Program in Humanistic Studies in Engineering is supported by grants from the National Endowment for the Humanities, the Ford Foundation, and the Rockefeller Foundation.

References

1. Mesthene, E. G., "Technology and Humanistic Values," Computers and the Humanities, Vol. 4, No. 1, September 1969.

2. Billington, D. P., and R. Mark, "Humanities in Civil Engineering," Journal of Engineering Education, Vol. 59, No. 9, May 1969.

3. Billington, D. P., "Engineering Education and the Origin of Modern Structures," Civil Engineering, Vol. 39, No. 1, January 1969.

4. Sachs, K., "A Finite Element Analysis of a Doubly Curved Gothic Vault," Ph.D. Dissertation, Department of Civil and Geological Engineering, Princeton University, Princeton, New Jersey, June 1971.

5. Le Corbusier, Toward a New Architecture, Frederick A. Prager, New York, 1927.

6. Giedion, S., Space, Time and Architecture, Harvard University Press, Cambridge, Fourth Edition, 1963.

7. Seyrig, T., "Le Pont sur le Douro," Mémoires et Compte Rendu des Travaux de la Société des Ingénieurs Civils, September and October 1878. An English translation of the major portion of this paper appears in The Engineer, Vols. 45 and 46, 1878, and Vol. 47, 1879.

8. Matheson, J., "Aspects," B.S.E. Thesis, Department of Civil and Geological Engineering, Princeton University, Princeton, New Jersey, April 1971.

9. Roy, H. E. H., "Toronto City Hall and Civic Square," ACI Journal, Vol. 62, No. 12, December 1965.

10. Mark, R., "Gothic Cathedrals and Structural Rationalism," Transactions of the New York Academy of Sciences, to appear.

11. Viollet-le-Duc, E. E., Entretiens sur l'Architecture, Paris, 1863, and 1872. Translated into English, by H. Van Brunt, Discourses on Architecture, J. R. Osgood and Co., Boston, 1875-1881.

12. Johnson, C. P. and P. G. Smith, "A Computer Program for the Analysis of Thin Shells," Structural Engineering Laboratory Report No. SESM 69-5, University of California, Berkeley, January 1969.

13. Bill, M., Robert Maillart: Bridges and Constructions, Frederick A. Prager, New York, Third Edition, 1969.

14. Billington, D. P., "Meaning in Maillart," VIA 2, the Student Publication of Fine Arts, University of Pennsylvania, Philadelphia, to appear.

15. Werner, H. R., Jr., "Kresge Auditorium: A Numerical Analysis and Criticism," M. S. Thesis, Department of Civil and Geological Engineering, Princeton University, Princeton, New Jersey, August 1971.

16. Esquillon, N., "The Shell Vault of the Exposition Palace, Paris," Proc., ASCE, Journal Structural Div., Vol. 86, No. ST1, January 1960.