VOL. 11, NO. 7, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

REDEFINING FOLDED PLATE STRUCTURE AS A FORM-RESISTANT STRUCTURE

Albertus Sidharta Muljadinata and A. M. Subakti Darmawan
Soegijapranata Catholic University, Semarang, Indonesia
E-Mail: sidharta@unika.ac.id

ABSTRACT

Folded plate structures should be redefined as form-resistant structures in which the folded-plate action is a combination of transverse and longitudinal beam action [1] p.264. The early generation of folded plate structure is marked with true folded plate structures. As the number and the variety of building form increases, classification based on form took place and being developed. This leads to confusion and false interpretation of folded structures. The confusion is shown from building examples. Roofing with either steel or pre-stressed concrete trusses were classified as folded structures. Origami could lead to another confusion, because it could be applied either as a building structure or as a non-structural member, such as ceilings and awnings. Based on the case of Sydney Opera House, and on other misleading folded structure building examples, a conclusion to stop the usage of the term "folded structures" has been recommended. Another recommendation is to separate building form categories from building structure classification.

Keywords: architecture, building structure, folded plate structure, form-resistant structures.

INTRODUCTION

The definition of Form-resistant Structures has been introduced and explained since 1963 by Salvadori [1]. His definition is as follows:
"Form-resistant Structures are structures in which strength is obtained by shaping the material according to the loads they must carry".

Two illustrations were put forward by Salvadori in his book (Figure-1(a) p. 295; and (b), p. 265):

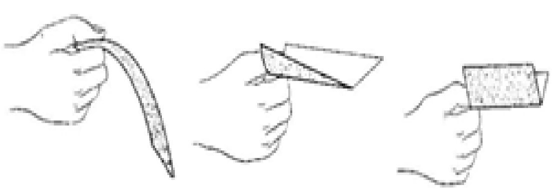


Figure-1. Form-resistant structure[1]: a/ Thin Shell b/ Folded Plate

Two Form-resistant Structures are thin shells (Shell Structures) and folded-plates (Folded Plate Structures). Engel considered those two structures as Surface-active Structure Systems in his book [2]. In line with the principles of the two previous mentioned authors, the concept of form-resistance by means of folded plates was brought earlier forward and discussed by Siegel [3]. This main stream structure principle of folded plate structures being a form-resistant structure is followed and supported by other structural experts, such as, Daniel Schodek [4]. However, in 1983, although he agrees with the mentioned principles, Schueller introduced a new classification system of folded plate structures [5], based not only on the structural system but also influenced by their forms. Curved geometry as well as curvilinear edges and hyperbolic paraboloids' structural behavior are being adopted. Furthermore, Sekularac, *et al*., developed Schueller's diagram of "Folded plate structure systems" into a diagram of "Forms of folded structures"[6]. Moreover, some building examples of the application of folded structures given by Sekularac, *et al*., from a structural point of view are not folded plate structures. This situation causes multi interpretations in the architectural education. The uncomfortable confusion leads to a fundamental research done by the authors to clarify and to find the truth about the matter.

The theory and true examples of folded plate structures

The theory of Folded Plate Structures consists of three approaches. The first approach is the application of Form-resistant Structure theory in folded plate structures. The second approach is the load transfer, and the third approach is the best material.

Form-resistant Structure principle in Folded Plate Structures: The key word here is "to be able to carry load". Depends on the load, a series of load is shown in Figure-2. (taken from Siegel, 1961, p. 197)

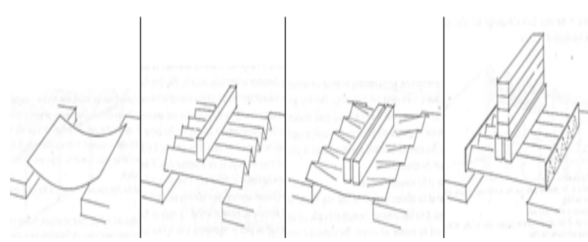


Figure-2. From left to right:
(a) A piece of paper without any fold could not carry its own weight. (b) After being folded the paper can not only stand between the gap, but also carry some extra weight. (c) When the load is being added, the folded paper need to be stiffened. (d) After the edges were stiffened, the structure could carry more load [3].

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

The Load Transfer: Load is being transferred through the inclined surfaces to the supports of the structure, as shown in Figure-3. Folded plate surfaces should not be put horizontally, because it would create moment.

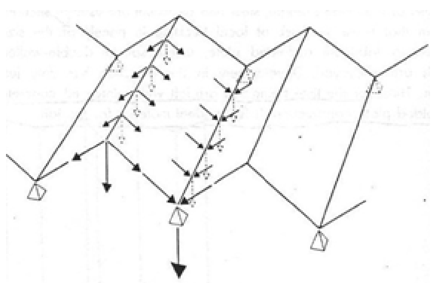


Figure-3. (taken from Siegel, 1961, p.198) Load is being transferred through the inclined surfaces to the supports.

Inclined surfaces is functioning as beam to carry load and as slab to cover activities below [2]. (cfr. Engel, 1981, p.132)

3. The Best Material: Reinforced concrete, i.e., to be stiff and monolithic (Siegel, 1961, p.197) or continuous (Engel, 1981, p.131). Although other material can also be considered as stiff, monolithic and continuous, the best material to carry load in building structure is reinforced concrete either pre-stressed, prefabricated or cast in place.

The application of folded plate structures flourished in Europe in the early 60's. Some examples in The Netherland was reported by Garcia[7] in the Second International Congress on Construction History at Queens' College, Cambridge University, in 2006, and two of them are presented below:

The folded roof over the Verenigd Plastic verkoopkantoor N.V. laboratory building in Zeist (1960). The folded roof construction is significant because it utilizes pre-stressing Freyssinet cables to meet its strength [7].

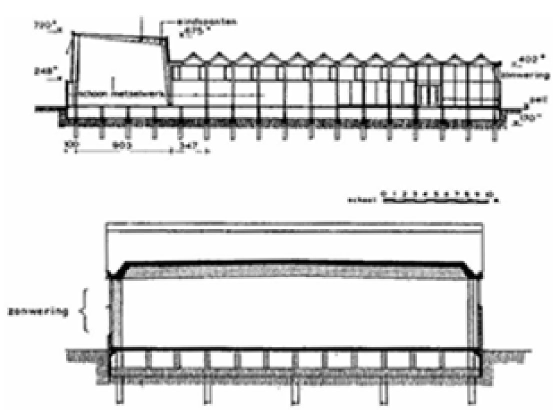


Figure-4. The Verenigd Plastic verkoopkantoor in Zeist[7]. (a) (top and centre): Longitudinal and transversal sections, (b) (bottom): Interior.

Precast concrete folded plate façade and roof of the Church in Hoensbroek, Heerlen (1964).

This building is of particular interest, because the folded plates were not cast in place, but precast in a shop [7].

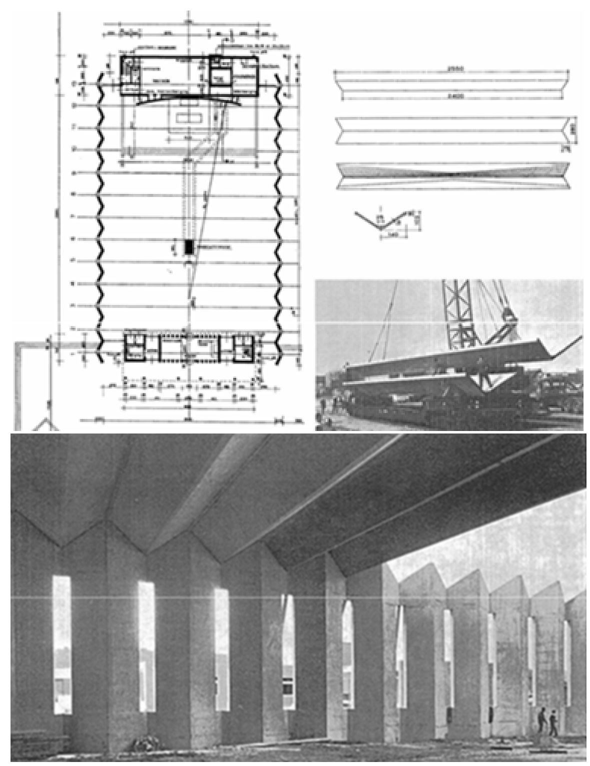


Figure-5. The Church in Hoensbroek [7].
(a) (top left): Plan, (b) (top right): Precast folded plate components, (c) (bottom): The building under construction.

The only true Folded Plate building in Indonesia was built between 1973-1977 in Jakarta, Indonesia. It is a Human Resource Development Centre.

VOL. 11, NO. 7, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Figure-6. The Human Resource Development Centre in Jakarta (top: taken in 2007; bottom: 2015 file).

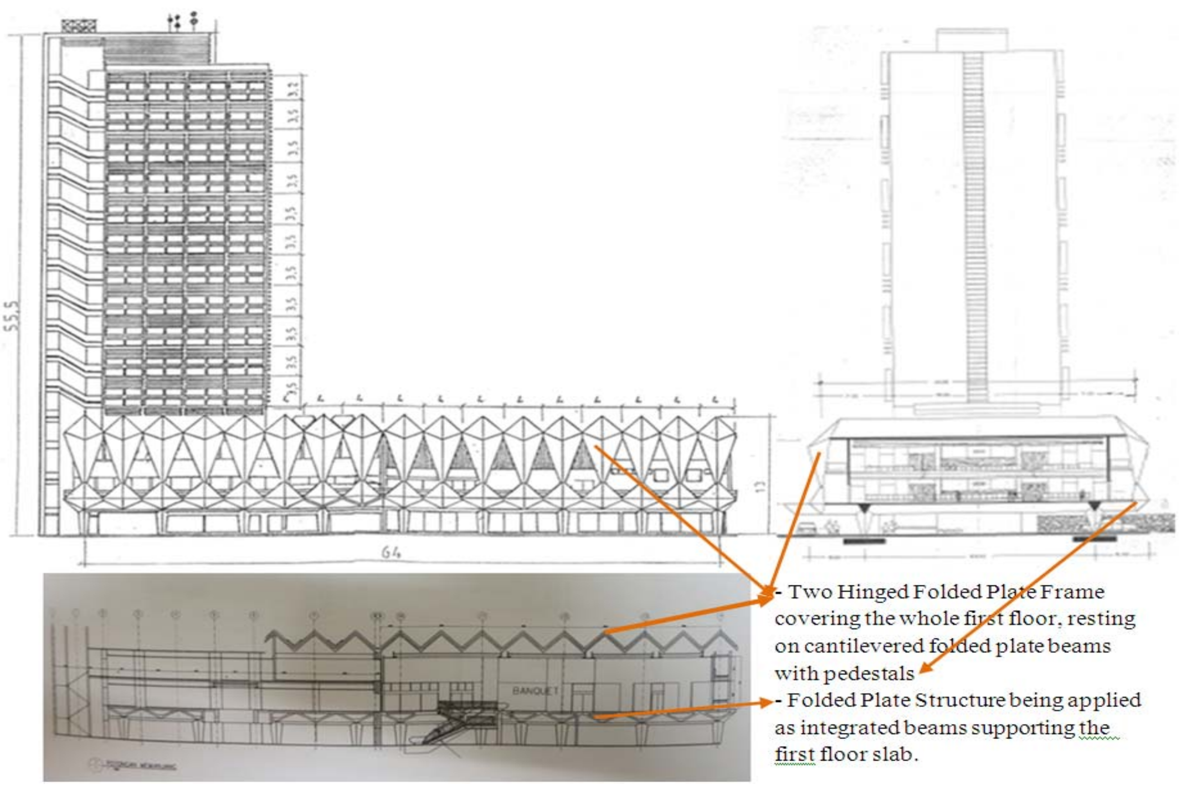


Figure-7. (Top left and right): North Elevation and Cross Section facing East of The HRD Centre in Jakarta[8]. (Bottom): Longitudinal Section of The HRD Centre, not showing the lodging tower.

In the HRD Centre in Jakarta, folded plate structure is being apllied not only for the roofing, but also as floor beams, which are integrated with the floor slab. The roof is also integrated with its supports, i.e., the façade columns. (cfr. the cross section) to become a "two-hinged folded plate frame" roof [8], as named by Schueller.

SOME CONFUSING EXAMPLES NAMED AS FOLDED STRUCTURES

While all true building examples with folded plate structure were built in reinforced concrete (cfr. Theory #3: The Best Material)), some confusing examples for folded structures introduced by Sekularac et. al., were buildings using steel trusses.

The elaboration of Folded Structures (not Folded Plate Structures) focuses only on building forms. No structural theory was mentioned. Sekularac definition of Folded Structure is as follows:
"a folded form of construction, including structures made of plates and structures made of sticks which make a folded form by their mutual relationship in space" [6].

Then, Sekularac added:
"Some authors also call a folded structure the origami construction".

Indeed, origami can be considered as a folded plate structure, that is, if the origami surfaces are developable and are carrying external load, i.e., being a structural system. In addition, the form of an origami design is certainly a folded surface. In the discussion following this part. an example of the application of non-structural origami will be presented.

Sekularac's confusing definition stated above has become more confusing when supported by the building examples he introduced. At least, three examples of folded structures mentioned in Sekularac's paper[6] are using trusses:

- The United States Air Force Academy Chapel in Colorado, USA,
- The Space Truss Roof Structure of the Transair Hangar in Gatwick Airport, London, UK, and
- The International Convention and Exposition Centre in Naning, China.

The United States Air Force Academy Cadet Chapel in Colorado Springs (1962).

The amazing building, designed by Walter Netsch from Skidmore Owings & Merrill (SOM) features a series of 17 glass and aluminum spires, each consists of 100 tetrahedrons, enclosing the upper chapel [9]. As seen in Figure-8, the tetrahedrons, although from both sides, the exterior and the interior, are providing a folding composition, are certainly not a folded plate structure. Structurally, this building belongs rather to space frame structures.

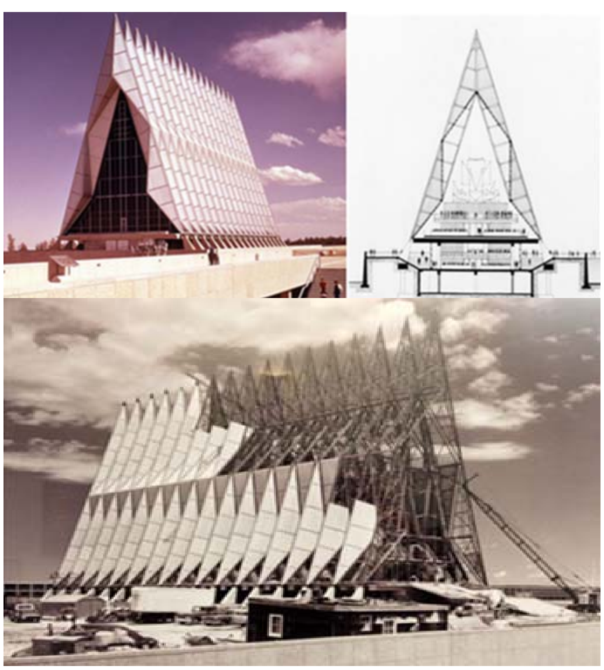


Figure-8. a/ (top left): The Chapel in used[9], b/ (top right): its section drawing[10], and c/ (bottom): during construction[11].

Sekularac is not the only one who uses this folded form building as an example. Schueller and Garcia mentioned also this building as a striking example for folded plate structure, which is, in the writers' opinion, very confusing. Schueller mentioned this folding formed building as one of another striking examples of the folding principle, but put the picture in the chapter of "The Frame Truss" ([5], p.288). Garcia reported this US Air Force Academy Chapel in her paper (p.1990), as one of the folded formed buildings with a "very complex combination".

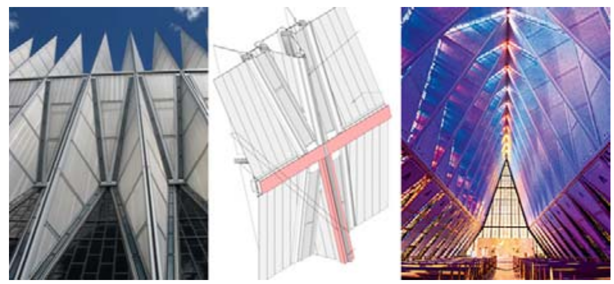


Figure-9. (left):The tetrahedrons as seen from outside [13]; (centre): The detail of the tubular frame[14]; and (right): the colorful glazed interior [12]. Photo by D. Merriam.

The Space Truss Roof Structure of the Transair Hangar in Gatwick Airport, London (1958).

Figure-10. (top): Front elevation of the Transair Hangar [15]; and Right: The roofstructure [15].

The roof structure of the hangar is a space frame construction. Figure-10 (right) shows more detailed

VOL. 11, NO. 7, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

picture of the folding pattern of the pre-stressed concrete trusses. The form of the triangle prismatic truss is very clear. Therefore, one might think that this building could be considered as a folded form building.

The International Convention and Exposition Centre in Naning, China (2003).

Figure-11. International Convention and Exposition Centre (ICEC) in Naning, China [16].

The round shape "great cupola" building is the central entrance building for the International Convention and Exposition Centre in Naning, China [16]. The roof structure is made of curvilinear trusses, i.e., a folding steel structure, covered by two layers of translucent membrane materials.

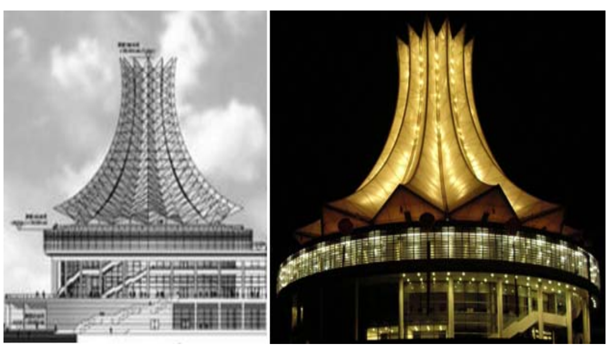


Figure-12. ICEC in Naning, China[16]. Left: Lattice folded structure roof of steel trusses[17]. Right: The roof structure being lighted from inside like a torch[16].

DISCUSSIONS AND CONCLUSIONS

Two different approaches toward folded plate structures has been presented. The first approach is based on its structural behavior, capacity and strength, and the second appreciation is based on the visibility of its folded form. Facts from the above examples are quite contrast. Building examples with true folded plate structures result in both, surface-active "form-resistant" structures and folded form structures. While the so-called "folded structures" confusing examples lead only to folded form structures, disregarding their structural features as folded plate structures.

Four folded form building cases will be discussed further in this part:

- The Osanbashi Yokohama International Passenger Terminal, a building example with origami folded ceilings.
- The Istora Senayan, a Sport Hall with a folded form roofing.
- The Miami Marine Stadium, a folded form building with a complex hyperbolic-paraboloid shell roof.
- The University of Illinois Assembly Hall (now: The UoI State Farm Center), a big hall with a folded plate dome.

The Osanbashi Yokohama International Passenger Terminal in Japan (2002).

The Osanbashi Yokohama International Passenger Terminal uses origami folded pattern for the ceilings. The origami form of the interior is very robust and very well made. (See Figure 13-14). But, the origami ceilings are decorative, not structural. They do not carry any structural load. The building main structure consists of a series of steel trusses, which are covered by the origami ceiling panels.

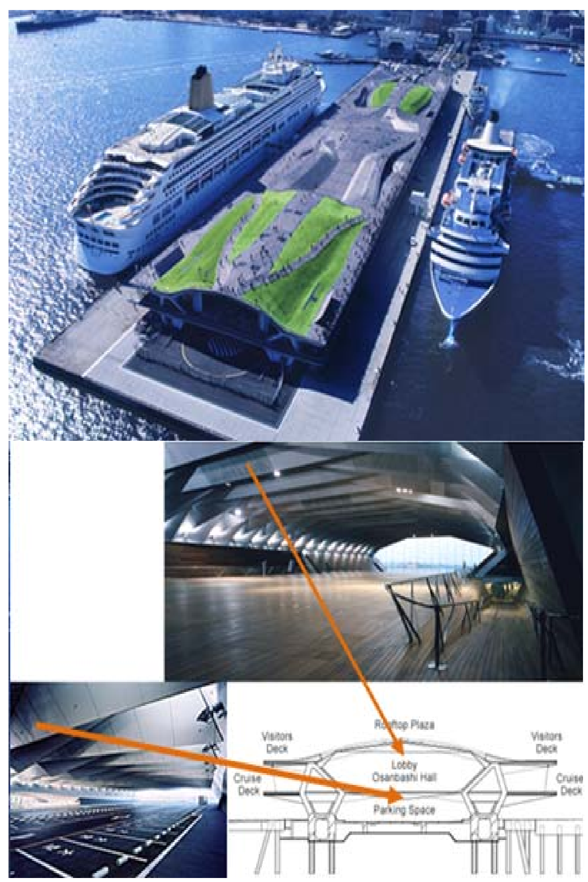


Figure-13. (top): Yokohama Port Terminal [18]; (centre): Lobby/Osanbashi Hall; (bottom left): Parking Space; (bottom right): A Cross Section of the Port Terminal showing the location of the origami ceilings.

VOL. 11, NO. 7, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Figure-14. (top): Illustration of the steel structure [19]; (bottom): the interior (left), and the perforated ceiling detail [20] (right).

The Istora Senayan in Jakarta, Indonesia (1962). The Sport Hall has a folded form roofing. But the carrying load structure is made of trusses (see Fig. 15 - right).

Figure-15. The exterior and the interior of Istora Senayan showing the folded roof [21] and its steel frame structure [22].

The Miami Marine Stadium in Florida, USA (1963).

This stadium has a very unique building form. The cantilevered roof was one of the largest spans of unsupported concrete in the world. Elevation from the land side looks like a folded plate roof, but from the water side it has a totally different appearance, i.e., like that of a flat roof (See Figure-16.).

Figure-16. Miami Marine Stadium. (top): Elevation from the land side[23]; (bottom): Seen from the water side[24].

To understand its structure and form one should analyze the section and break down the elements. The roof structure comprises of 8 sets of a combination of four hyperbolic-paraboloid shells with straight edges. Each set of four hypars is supported by a set of three columns, one in the centre (main interior column) which bears the entire weight of the four hypars, and two at the back (diagonal tension columns), preventing the thin shells from tilting.

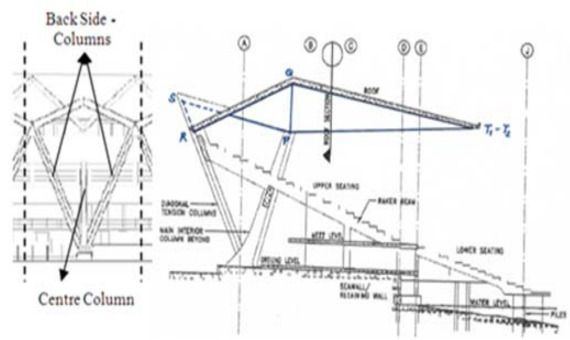


Figure-17. The Structure of Miami Marine Stadium.
a/ (left): One of the 8 structural bays seen from the land side, showing the set of three columns;
b/ (right): Cross section of the stand and the roof, showing thr srt of three columns and the straight edges of two hypars seen from this side
(PQ-QR-RS-SP and PQ-QT_1-T_1T_2-T2P).

Therefore, this stadium has a shell structure roofing, not a folded plate structure one, although from the building form point of view this building might be considered as a folded form building – as mentioned by Schueller:
"Folded plate structure can be organized from the following points of view …
- Geometry;\
- Construction: …
- Material: …
- Structural behavior:
beams, arches, frames, surfaces, vaults, shells of various forms (e.g., domes, hyperbolic paraboloids), intersecting forms, etc." [5] p. 367-369

The University of Illinois State Farm Center in Illinois, USA (1964).

VOL. 11, NO. 7, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Figure-18. The University of Illinois State Farm Center: (top): Exterior view during the day [25]; (bottom): The extraordinary view of the "Flying Saucer"-shaped building at night [28].

The "Flying Saucer"-shaped University of Illinois Assembly Hall roof is the first concrete dome sport structure and a rare folded plate dome concrete structure in history. Even Schueller left the space for building example of Folded Plate Domes in his book (1983, page 368) remained unfilled (cfr. Appendix-I).

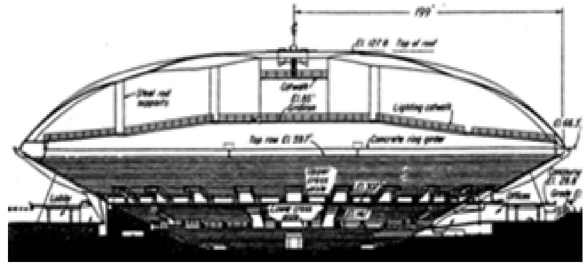


Figure-19. (top): The folded plate dome under construction [26]; and (bottom): A cross section of the hall [27].

The dome spans 120 m' and is made of ribbed reinforced concrete in a folded-plate design that tapers to a thickness of mere 8.75 cm'. The dome was first cast-in-place on falsework (Figure 18b). The compression ring-beam on which the folded plate dome was placed was post-tensioned prestressed by wrapping 988 km of 6.35 mm steel wire under high tension around it. This made the dome self-supporting and being considered an engineering wonder, because the prestressed concrete was applied in a way it had never been used before. The dome was the first of its kind. The post-tensioned compression ring counters the thrust from the dome. The ring is supported by forty-eight massive reinforced-concrete radial buttresses cantilevering above the glazed lobby and exposition space. This design provides a special character of the building at night. By lighting the building's underside entirely from interior sources, the light that floods out of the glass walls produces the effect of the dome hovering over the ground (Figure-18d).

From the presentation and discussion, it can be understood that a building that has a folded form does not have to be a building with folded plate construction. On the contrary, a folded plate structure building always features a folded form building. The interrelationship between the two is presented in the Table (of Buildings Presented and Discussed) shown in Figure-20.

No.	Building	Picture	Folded Form Building	Folded Plate Structure (System, based on Schueller)
1	The folded roof over the Verenigd Plastic verkoopkantoor N.V. laboratory building in Zeist, in The Netherlands. (1960)		Yes	Yes (Folded Plate Surface – Linear)
2	Precast concrete folded plate façade and roof of the Church in Hoensbroek, Heerlen, in The Netherlands. (1964)		Yes	Yes (Folded Plate Frame – Continues)
3	The folded roof, façade, and floor of The Human Resource Development Centre in Jakarta, Indonesia. (1977)		Yes	Yes (Folded Plate Frame – Two Hinged)
4	The United States Air Force Academy Cadet Chapel in Colorado, USA. (1962)		Yes	No
5	The Space Truss Roof Structure of the Transair Hangar in Gatwick Airport, London, UK. (1958)		Yes	No
6	The International Convention and Exposition Centre in Naning, China. (2003)		Yes	No
7	The Osanbashi Yokohama International Passenger Terminal in Japan. (2002)		Yes	No
8	The Istora Senayan Sport Hall in Jakarta, Indonesia. (1962)		Yes	No
9	The Miami Marine Stadium in Florida, USA. (1963)		Yes	No
10	The University of Illinois State Farm Center in Illinois, USA. (1964)		Yes	Yes (Folded Plate Dome)

Figure-20. Table of Buildings Presented and Discussed.

The situation is similar to the well known Sydney Opera House (SOH) [21], which should not be considered as having a shell structure for its roofing. In terms of its form, SOH suits very well as having a multi-shell-form building. However, the structure of the shells in SOH could not be considered as shell structure.

The definition of thin shells (structures) according to Salvadori[1] (p.296) are:
"form-resistant structures thin enough not to develop appreciable bending stresses, but thick enough to carry loads by compression, shear, and tension".
Siegel[3] (p.214) stated further, that,
"the shell must be 'very thin' in relation to the span', and 'the shell ought to be made so thin that it is incapable of resisting any forces other than those acting in tangential directions."

Siegel also mentioned other requirements of shell structures, i.e.,
"Shells are rigid and curved" [1] (p. 213).

The shell surfaces of Sydney Opera House failed to fulfill the definition of thin shells, because the outer surfaces are just like a skin that cover the structure underneath. The main structure comprises of three hinged arches which are arranged one next to the other, narrow at the bottom and widen at the top like a fan (see Fig. 21-top right).

ARPN Journal of Engineering and Applied Sciences

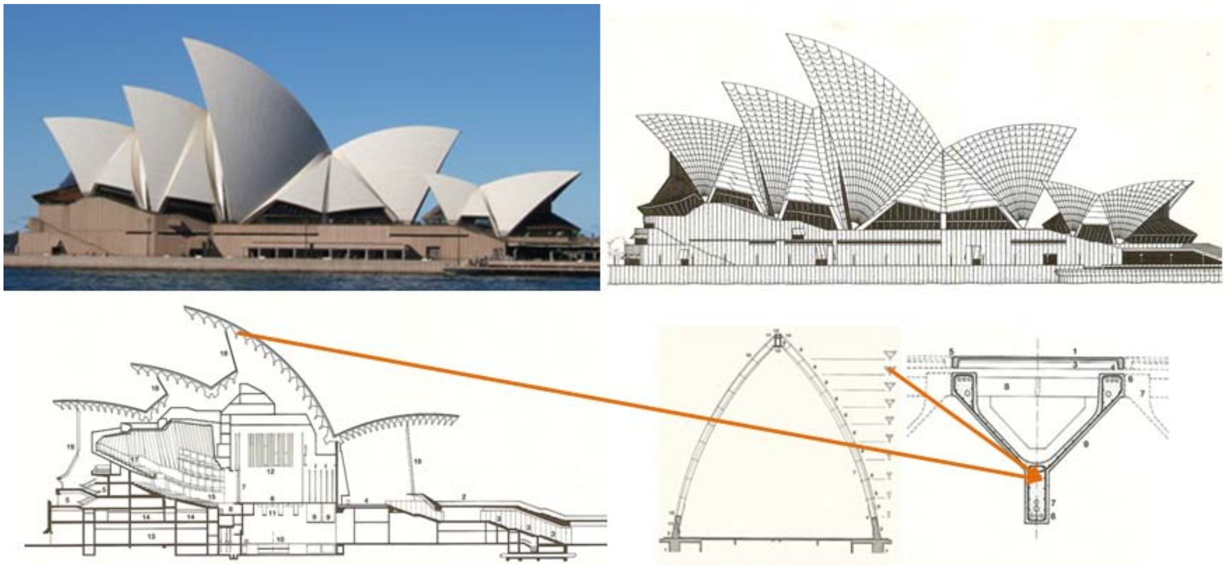


Figure-21. Sydney Opera House. Top left: Seen from a distance; Top right: Elevation showing the ribbed shell surface[29]; Bottom left: Longitudinal section; Bottom right: The three-hinged arch main structure, and the detail of the split-arch beams at the top, where outer panels are fixed [29].

Learning from the misleading appearance case of SOH in deceiving its spectators to believe in the different structure, the definition of folded plate structure should also not be confused with the building form appearance. Building structure is about how to manage forces. Its form is a result of the chosen structure and material. Therefore, as a consequence, it is the logic of the structure which leads the form, and not the other way round. Talking about building forms without considering their structure behavior and characteristics would create confusion.

Some recommendations are as follows:

- The definition of folded plate structure should be redefined as a form-resistant structure to meet the characteristics of the folded and inclined plates in terms of load transfer and structural behavior, and certainly not in terms of the building folded form.
- The confusion about folded plate structure being misunderstood, because of the existence of many folded form building with different kind of structures, should be put on halt.
- The misleading term "folded structures" in part III should be reconsidered. Terms such as "folded form buildings" should be more appropriate to replace the misleading term, because the word "structure" is more associated with building structural matters rather than building form.
- The structural knowledge should not be ignored when analyzing folded form buildings. Many folded form buildings which are using 'sticks' – as mentioned by Sekularac – belong to Space Frame Structure. In fact, space frame structure is able to create almost all kinds of building forms, including folded form buildings.
- Therefore, building form categories should be separated from building structure classification.

ACKNOWLEDGEMENTS

The authors would like to thank the Director of Research and Community Services, Directorate General of Higher Education, Ministry of National Education Indonesia, for the opportunity and funding to do this fundamental research on folded plate structure.

REFERENCES

[1] Salvadori M. and Heller R. 1963. Structure in Architecture. Prentice Hall, Inc. New Jersey, USA.

[2] Engel H. 1981. Structure Systems. Van Nostrand Reinhold Company. New York.

[3] Siegel C. 1961. Structure and Form. Crosby Lockwood & Son Ltd. London, UK.

[4] Schodek D.L. 1993. Struktur, Edisi Kedua. Subagdja D. (Ed.). Penerbit Erlanga. Jakarta, Indonesia.

[5] Schueller W. 1983. Horizontal-Span Building Structures. John Welley & Sons. New York, USA.

[6] Sekularac N. Sekularac J.I. and Tovarovic J.C. 2012. Folded Structures in Modern Architecture. Journal of Architecture and Civil Engineering. 10. 1.

[7] Garcia R. 2006. Concrete Folded Plate in the Netherlands. Vol. 2. Proceedings of the Second International Congress on Construction History. p. 1189.

[8] A. S. Muljadinata A.S. and Darmawan A.M.S. 2015. Redefining Folded Plate Structure as a Form-resistant Structure. Proceedings of the First International Conference on Science, Technology and Interdisciplinary Research. p. 27.

[9] S.O.M. US Air Force Academy Cadet Chapel in Skidmore Owings & Merrill LLP [Online] Available: http://www.som.com/projects/us_air_force_academy__cadet_chapel

[10] Perez A. 2010. AD Classics: USAFA Cadet Chapel / Walter Netsch of Skidmore Owings & Merrill. J. ArchDaily. [Online]. Available: http://www.archdaily.com/63449/ad-classics-usafa-cadet-chapel-skidmore-owings-merrill-2/

[11] Ruud C. United States Air Force Academy Cad

et Chapel under construction. [Online] Available: https://www.pinterest.com/pin/322640760779750003/

[12] Merriam D. 2008. Preservation-Magazine. [Online] Available:

[13] http://www.preservationnation.org/magazine/2008/may-june/air-age-gothic.html#.Vb6KqfOqpHw Photo: http://www.preservationnation.org/assets/photos-images/preservation-magazine/2008/may-june/feature-airforce01.jpg

[14] Panoramio Google Maps, Photo taken in United States Air Force Academy [Online] Available: https://ssl.panoramio.com/photo/8101672

[15] Solla I.F. 2011. Cupples Products: A Tall Tale of American Curtain Walling. Façade Confidential, [Online] Available: http://facadesconfidential.blogspot.com/2011_12_01_archive.html

[16] Campbell B. 1958. The new airport at Gatwick. Concrete Quarterly. 37.2.

[17] Schlaigh Bergermann und Partner. Naning International Exhibition and Convention Centre. [Online] Available: http://www.sbp.de/en/build/sheet/1005-Nanning_International_Convention_and_Exhibition_Center.pdf

[18] Profile 51 Arch. [Blog Online] Available: https://plus.google.com/photos/+51arch51arch/albums/5719190942054239713/5719190972319444002?pid=5719190972319444002&oid=112118491756972430186

[19] Osanbashi Yokohama International Passenger Terminal. Official Website Information. Available: http://www.osanbashi.com/en/

[20] Uhl J. and Fano D. 2009. Detail Study of Yokohama International Passenger Terminal by FOA, Yokohama, Japan. Available: http://www.jasoneroberts.net/yokohama

[21] Interior of Yokohama Port Terminal, Available: http://www.flickriver.com/photos/jietcomm/581508981/

[22] Wikipedia. Istora Bung Karno. Available: https://id.wikipedia.org/wiki/Istora_Gelora_Bung_Karno

[23] Djarum Badminton. Penonton Padati Bio 2015. Available: http://www.djarumbadminton.com/indonesia-open/berita/read/penonton-padati-hari-pertama-bio-2015/

[24] The American Institute of Architects. 2010. Structure and Sculpture Under Construction: Hilario Candela's, FAIA, Miami Marine Stadium. 17. Available: http://info.aia.org/aiarchitect/2010/multimedia/slideshows/Miami-Marine-Stadium/Miami-Marine-Stadium.html

[25] Forbes D. 2015. Miami will spend Up to $16M on Miami Marine Stadium Grounds. Available: http://dforbesre.com/miami-will-sp0end-up-to-16M-on-miami-marine-stadium-grounds/

[26] State Farm Center, Illinois Renaissance (Assembly Hall). Available: http://www.esdglobal.com/gallery/project/659-state-farm-center-illinois-renaissance-assembly-hall

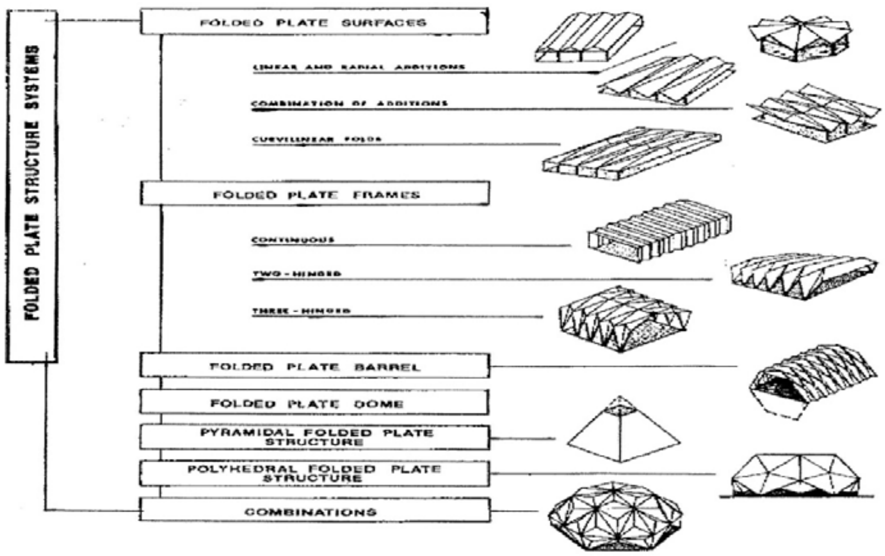
[27] Aronson D. 2013. Memory Lane: Beam Us Up. Illinois Alumni Magazine. Available: https://www.uiaa.org/illinois/news/blog/index.asp?id=659

[28] Groundhogday. 2012. Dome of University of Illinois "bowl" rises 128 ft above the arena, which is 24 ft below grade. Fighting Illini Basketball. Available: http://www.illinoisloyalty.com/Forums/showthread.php?p=542786

[29] Nomarandlee. 2012. Assembly Hall, University of Illinois at Urbana-Champaign. SKYSCRAPERCITY.COM. Available: http://www.skyscrapercity.com/showthread.php?t=1515930&page=3 Drew P. 1995. Sydney Opera House: Architecture in Detail. Phaidon Press Limited. London.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

APPENDIX-I



Schueller's Folded Plate Structure Systems [5] p.368.