Structural System in Architecture
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Lecture No -35
Waffle Slab and Folded Plate Structures

Welcome to the online NPTEL certification course on Structural Systems in Architecture. Today we are on the verge of module 7, the week 7 that is on the tensile and the plate structure and today we will discuss lecture number 35 that is the last lecture on module 7, waffle slab and the folded plate structure. If you remember in the last lecture. We introduced the plate and in that plate we have also introduced the two typical variety of the plate and that is called a flat plate structure and the flat slab structure. Today we will initially discuss on the waffle slab and then the folded plate. So, the basic concepts to be covered are:

- Introduction to Waffle Slab
- Classification of Waffle Slab
- Grid Geometry of Waffle Slab
- Advantages of Waffle Slab
- Applications of Waffle Slab in Architecture
- Introduction to Folded Plate Structure
- Folded Plate Action
- Types of Folded Plate Structure
- Applications of Folded Plate Structure in Architecture

The intended learning objectives are:

- Outline the Structural Concept of Waffle Slab and Folded Plate Structure.
- Illustrate the types, parts and functions of Waffle Slab and Folded Plate Structure.

So, let us start with the introduction of a waffle slab. the waffle slab is one typical type of slab, or we can say it as a plate, which are eventually made with the consistent monolithic beams. Monolithic beams are regular and very common for all the slab. But in this case, it will be very closely spaced concrete and the joist or the beams are monolithically casted with the slab. So, it is a totally integrated system with the casting.

When we cast a slab, there are two directional or maybe unidirectional, the members of the ribs or that joist come together in action of that structural system. The waffle slab is also known as the coffer slab. In Figure-1, a typical waffle slab is shown.

Figure 1 : waffle slab

So, what happened in the waffle slab, in case of this particular structural system of the waffle slab, those densified beams or the ribs will actually effectively increase the depth of the structure. So, what is actually mentioned over here, the depth of the structure will be increased effectively. The geometry of the ribs will be governed by the total dead load, and overall span of the loading. As it is a long span beams, because of that the deflection is too much and that is why the beams are heavily reinforced. The ribs are kept as minimum of 125 mm wide and 900mm grid separation distance. However, that can vary for different types of span and different type of loading criterias. Now let us discuss about the type of waffle slab.

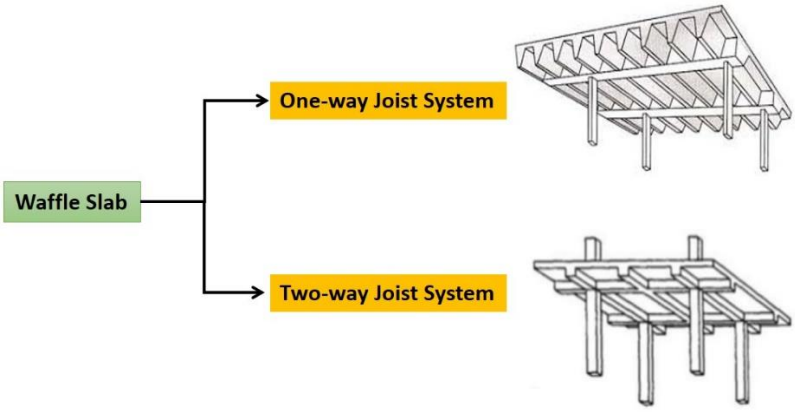


Figure 2 : types of waffle slab

From structural point of view or the load action point of view, the waffle slabs can be divided into two types. The first one is called the one-way joist system and the second one is the called two-way joist system, as shown in Figure-2. The joists are nothing but those ribs or the densified beams which are spaced very closely to each other to create a heavy deck.

In case of one-way joist system, the beam spanning is only in one direction, the ribs are very slender in that case and this will actually support the slab. This is suitable for long span applications. In case of long span application; economical range is almost about 30 to 50 feet and those voids which creates as I told in the earlier slide, it will increase the effective depth or in other way around if you see it will actually reduce the dead load. The electrical and the mechanical services can be passed through the voids.

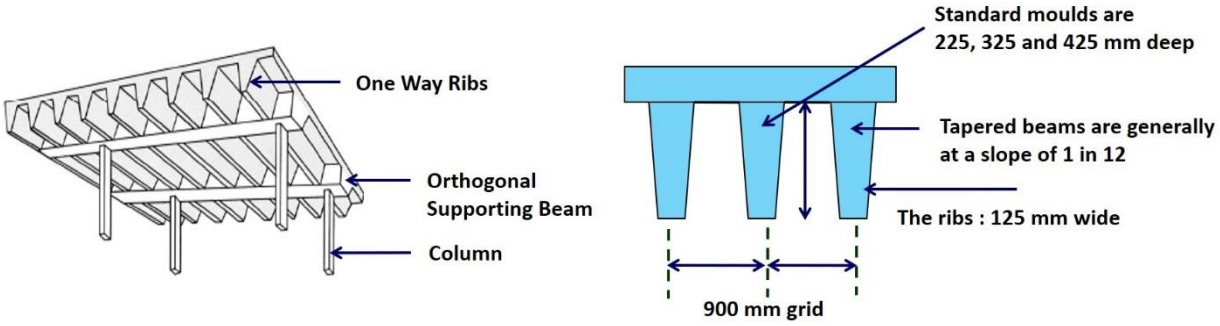


Figure 3 : the one-way joist system of waffle slab

In the right-hand side image of Figue-3, I have drawn the spacing, the spacing is almost about 900 mm, and the depth of the ribs will be like 225, 325, 425 mm like that; depending upon the amount of loading and span. The beams are tapered or sometimes it may be rectangular, and that depends upon the necessity of or demand of the interior. In general, on an average the ribs are around 125 millimeter wide. Whenever we have to transfer the load or discharge the load through a column, we give a beam crossing the direction of one-way joists and the beam on top of columns will actually bind the one-way joists.

Similarly, when the load is raised or span is increased; instead of going with the one-way system we can go for two-way system. Here, the ribs are in both directions, and it is also suitable for long span application. The economical range is almost 40 feet to 250 feet easily it can accommodate. The voids, those grids can be used to reduce the deadload of the structure and it will give you a very attractive ceiling appearance. Because those voids square or rectangular voids can create by the virtue of the two way joist system and those voids can be utilize for interior decorations, better

ceiling lighting etc. In case of one-way void system or one way a ribs system, what we have seen is, through the long voids the service conduits (electrical, plumbing etc.) can be adjusted.

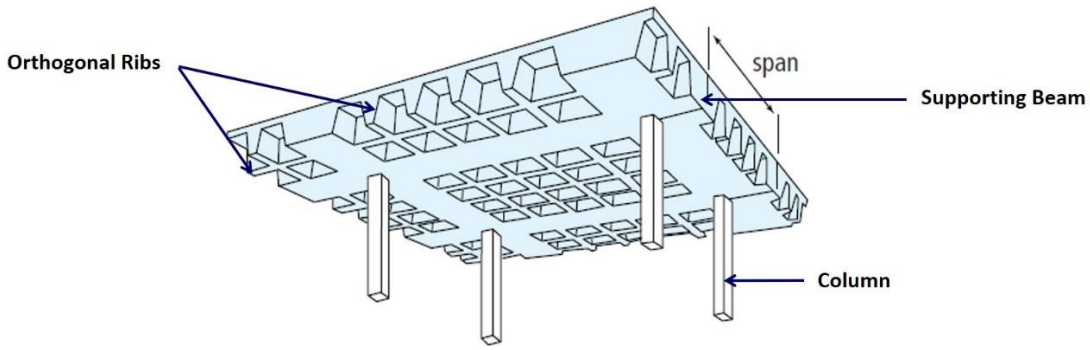


Figure 4 : two-way joist system

But in two-way system it is a bit difficult, and all such services either has to put below the slab or else place it inside.

Now let us go to the grid geometry of the waffle slab. The grids of a two-way slab can be of various types. Depending on the plan it can be classified as: Square grid, Rectangular grid, Skew grid and Diagonal grid. The choice of grid pattern is decided based on the overall dimension of the space and stiffness criteria. The square grids are easy to handle. The ribs intersect each other at an angle of 90º. As it is square, the x dimension and y dimension of the grid is equal.

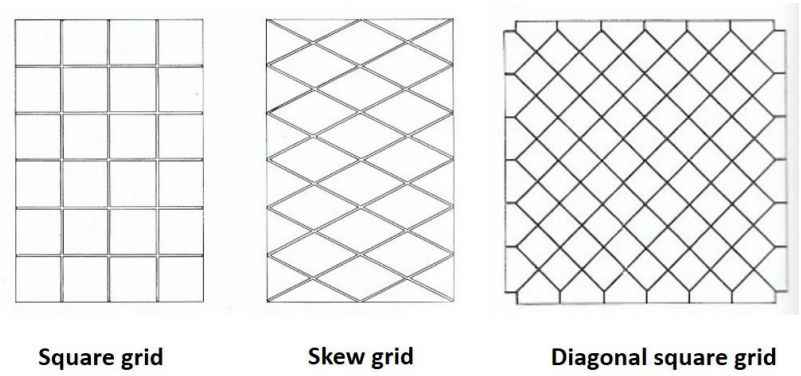


Figure 5 : grid geometry of two-way waffle slab

In skew grid system, the ribs do not intersect each other at 90º, resulting into skewed voids. Sometimes we can go for diagonal square grids in which the grid is square grid but they are in 45º orientation.

The waffle slab design is associated with three major parameters.

i. Geometry of Beam Pattern
ii. Grid Relationship to Lateral Space Enclosure

iii. Consistency of Beam Grid Structure

The first one, the geometry of beam pattern is important while we are going to design the two-way slab. Whether it will be a square grid, or rectangular grid, or oblique grid and what should be the depth etc. should be a major concern.

The geometry of the beam pattern that we have just discussed that it may be oblique it may be biaxial kind of a load transfer. The geometrical pattern of the ribs are considered for the load transfer mechanism. For that, if we want to have a equal amount of area almost equal amount of edges or equal amount of dimension for a particular area to be covered with the coffered slab, then we go for either rectangular or square grid, which will transfer the load in the perimeter beam in a biaxial action.

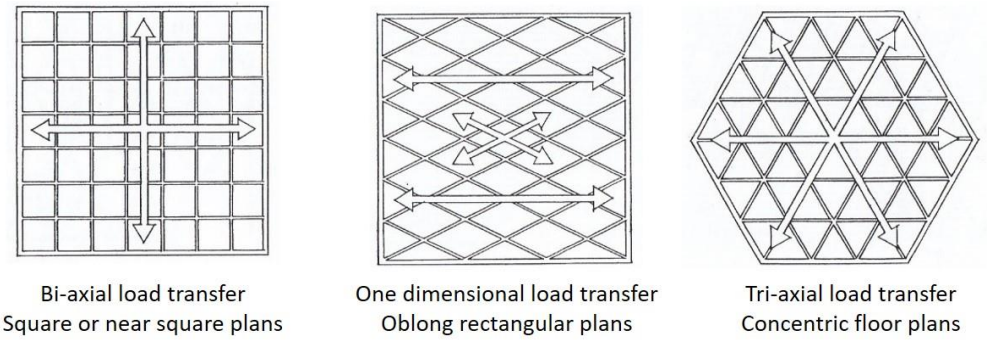


Figure 6 : the load transfer mechanism of two-way waffle slab

But the same area of the equal dimensions, or is more or less equal dimensions can be thought of in a diagonal grid or oblique grid too. Then it will actually be going to give a two way of opposite side two-way load share or it is also known as the one-dimensional load share. Sometimes we can go with a hexagonal kind of an area which can actually come under the coffered slab with a triangular grid pattern, in this case it transfers will be formed in that triangular load transfer as shown in Figure-6. So, this geometry of the beam pattern which depends upon the grids or the amount of area or the dimensions you have.

The grid relationship to the lateral space enclosure is another criteria where we can go for any kind of a grid or we can choose any type of grid. As I have also discussed earlier that the enclosure area if it is square you can go for any kind of rectangular or maybe oblique diagonal geometry. But if the enclosure area is circular or maybe a kind of a hexagonal shape or if it is a narrow rectangular shape, then we have to decide that which type of grid is required.

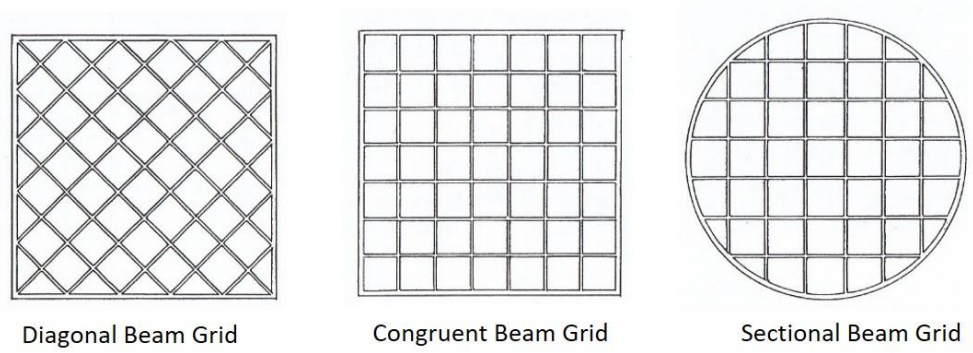


Figure 7 : grid relationship to the lateral space enclosure

Next is the consistency of the grid of the structure, consistency of the grid of the structure is something like that if we go further 1 degree ahead of thinking how the ribs dimensions will be, so the first can be thought of a homogeneous grid where the ribs dimensions or spacing's are all equal absolutely there is no change. But next is a graded grid separator or primary grade or the secondary grid also can be thought of. In the middle image of Figure-8, so if you see, there are lines which are having the primary locations of the grid and those primary locations of the grid are further subdivided to the smaller grids with the thinner ribs.

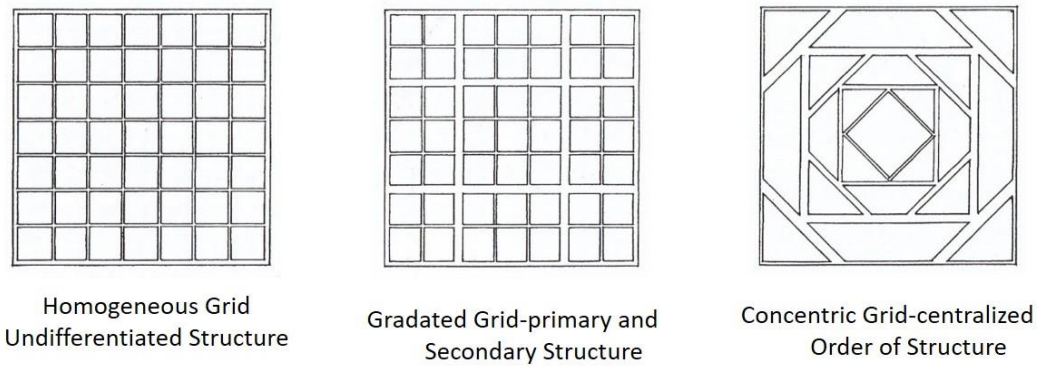


Figure 8 : consistency of beam grid structure

Finally, we can go for the concentric grid or centralized kind of a concentric grid. In that case, the ribs are not in a perfectly oriented 90º. They are oriented in different shapes and finally the dimensions or the length of the grid is gradually going to reduce and then finally go into the central location or to the center.

Let us go to the advantage of the waffle slab. The advantages are:

- It is flexible.
- Speedy construction can be gained.
- Easy for services integration.

- Gives good ceiling appearance.
- Robust and Durable.
- Fire-resistant.
- Cost effective for long spans**.**

The major applications are in:

- Airport
- Auditorium
- Large Halls: Gallery, Banquette
- Hotels

Now let us go to the application of the waffle slab in architecture. The master architect Louis khan, one of his works if you see, it is in the Yale University art gallery, shown in Figure-9. Where he has designed the waffle slab as exposed ceiling playing with the lighting for wonderful interior design.

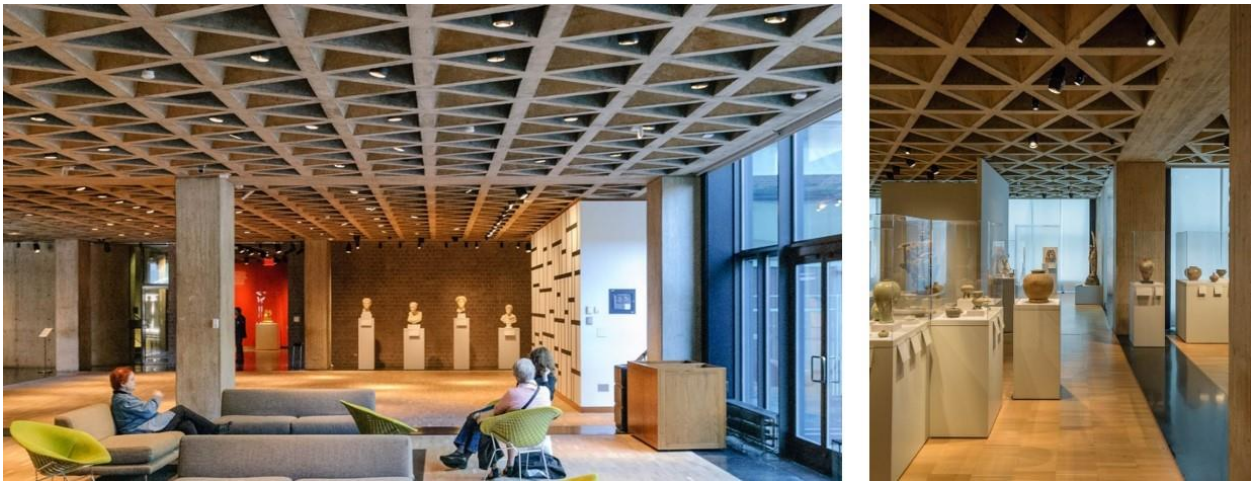


Figure 9 : the Yale University Art Gallery

The next one is from history of architecture, we have seen in the Pantheon, Rome which waffle slab grid structure with a dome. The Chatrapati Shivaji International airport, Mumbai If you have gone to that particular the airport, the columns are merged with coffered slab structure, looks very interesting, and from a circular column the grids or the coffered slab is blooming out like mushroom. Refer Figure-10.

The Pantheon, Rome

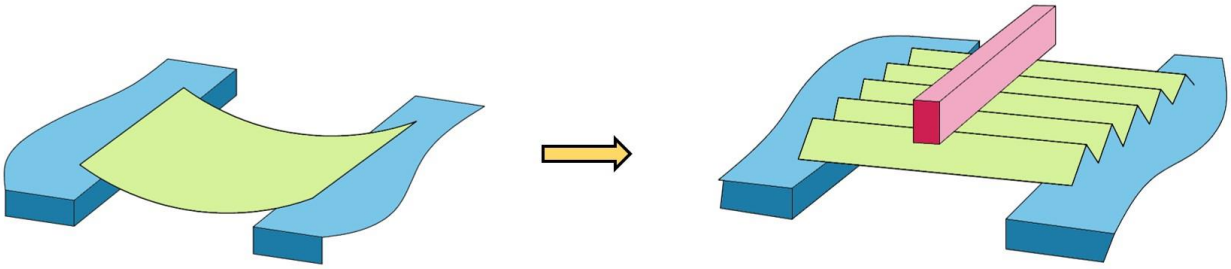
Chhatrapati Shivaji International Airport Mumbai

Figure 10 : examples of waffle slab structures

Now, we will go to the folded plate structure.

A folded plate is an example of a 3-dimensional or space structure made by composition of strips of plates. The assemblies of flat plate components are rigidly connected together along their edges. The geometrical profile of folded plate adds additional stiffness to the structural system. Also called as form-resistant structure. Folded plate action is combination of transverse and longitudinal beam action.

So, if you see the folded plate action, suppose there is a paper and there are two supports on two ends, as shown in Figure-11. In the first case, the left-hand side image, the paper will bend because of its own weight or self-weight.



Plain paper: Unable to carry self weight

Folded Paper: Able to take self weight and some additional some load

Figure 11 : the folded plate action - I

But if you can just make the paper into multiple folds, then you put some weight on it then it will be able to take its own weight and the additional weight. This kind of experiment you can do by yourself.

Then, if you increase the load on it; if you just compare the Figure-11 and Figure-12, we see that if you increase the load instead of the one if there are two such bars the whole system will fail

because of the additional load on it. But if at the transverse direction or at the edges if you increase the stiffness by the edge stiffener then it will become stronger. If you can add to such stiffener to the folded the papers, it will again give you more rigidity.

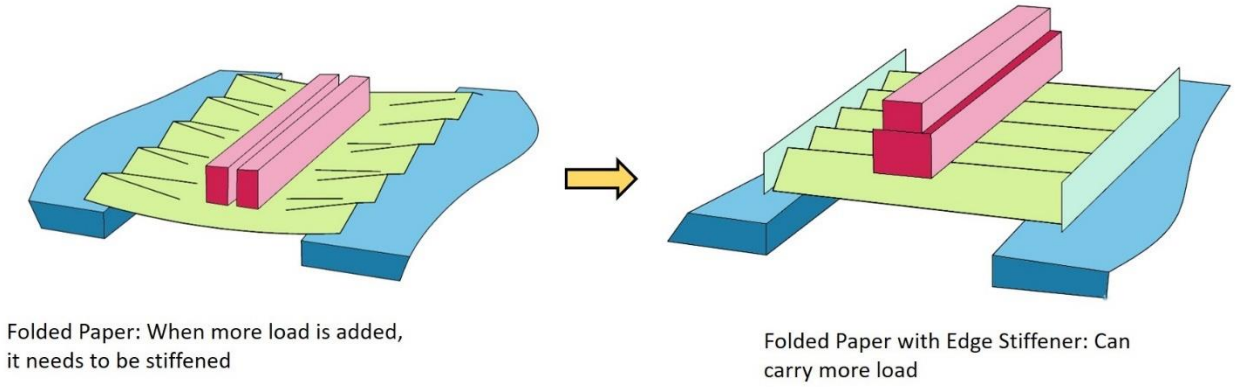


Figure 12 : the folded plate action - II

Basically, if you go through these two figures, Figure11 and Figure-12, then you will see that the same material almost with same span can take better load if it is folded. So that is why a folded plate can be applied in longer spans instead of a flat plate.

So, what happened in this folded plate is if you see very carefully in Figure-13, the left-hand image, those are the single plates and they are oriented in some angles, creating a triangular kind of a folder trait. So, the bends and its corner are actually the stiffener, because of this bend you have a stiffening effect and overall, the load carrying capacity of the system will increase.

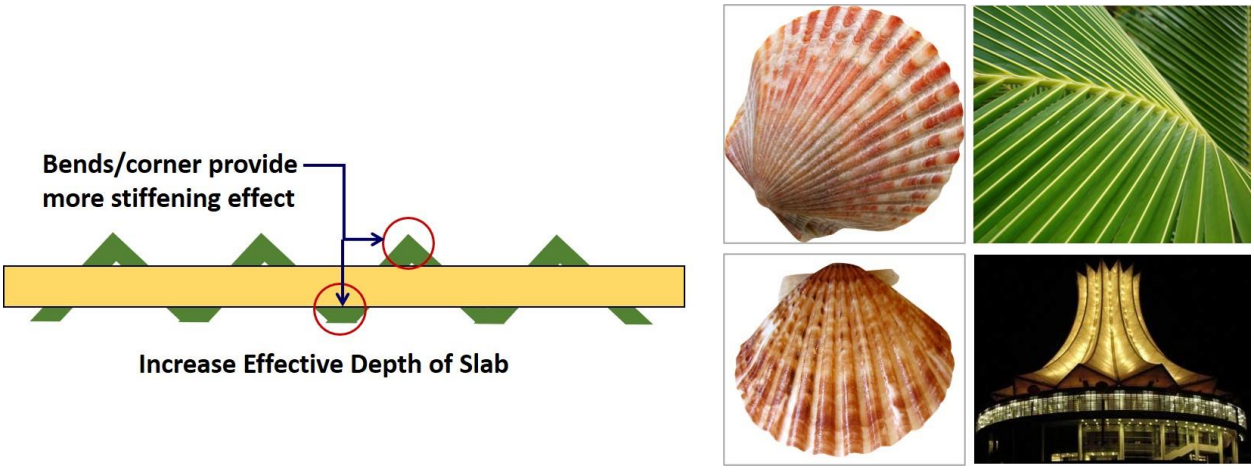


Figure 13 : concept of folded plates

Why is it going to increase? Because it will act as a single slab and the effective depth of the slab is virtually going to increase. Even if you not physically increase the slab depth but it will increase, because of the folds in ups and down directions or the crest or the valleys. Those are the

fundamental structural concept, where from the folded plate has been derived and it increases the virtual depth of the structure. There are many applications of folded plates in architecture. There are many examples in the nature also. The one of the things we will now going to discuss is the coconut leaf.

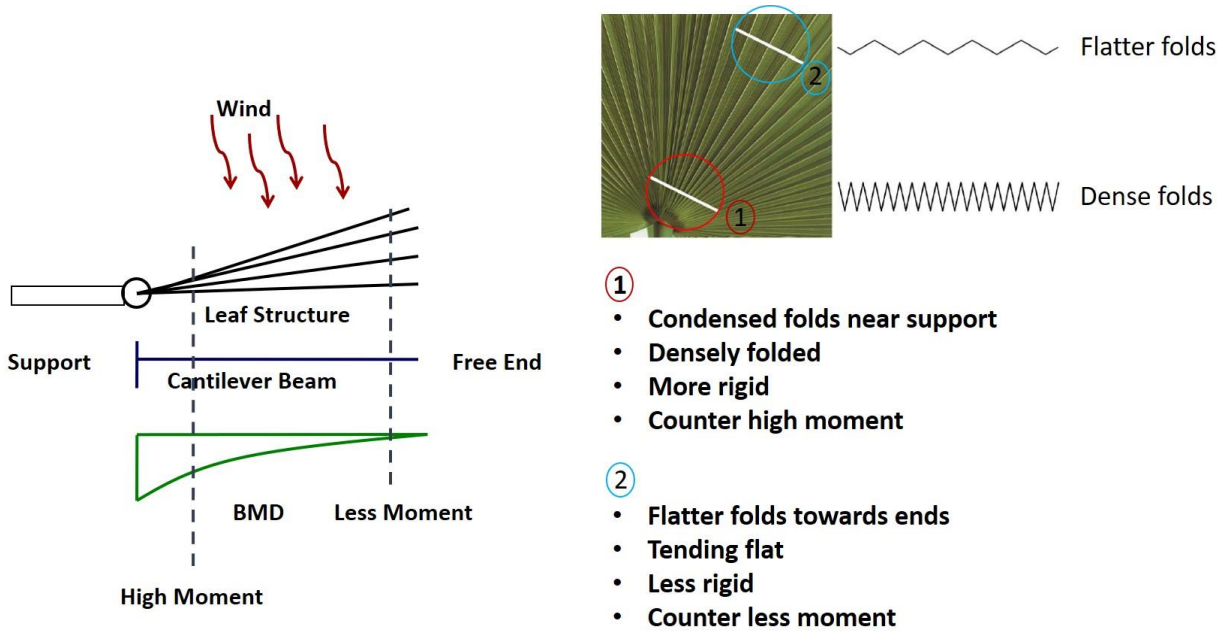


Figure 14 : the folded plate example in nature-the coconut leaf

If you see very minutely a coconut leaf as shown in Figure-14, the right hand side image marked as 1 and 2. If you see the section 1 it is a dense fold because it is very near to the end; and if you take the section 2, it is a very flattered fold which is along the other free end of that coconut leaf or the palm leaf. Now I have drawn a particular thematic diagram, the left-hand side image, where those lines are actually going to represent the folds. The stem and the leaf joint is also shown schematically, and it will have a cantilever action. So, it will have the fixed point, the support and the free end; which is also shown schematically. Under the wind or any kind of the external loading on the cantilever beam or this particular leaf, the bending moment diagram is like that. The bending moment diagram is heavy near to the support or near to this particular Junction where the leaf is actually started. Because of that, near this the support point is having a very high moment and at the end it will have less moment. Now if you compare this flatter fold and the dense fold of this particular leaf, the it has condensed folds near support, densely folded, more rigid and counter high moment. Whereas towards the flatter end, it is tending flat, it is less rigid and counter less moment

So, see the nature has also created the folded plate by virtue of the densified fold it can actually resist high amount of moment, where as in the case of the flatter case, it is not that much capable.

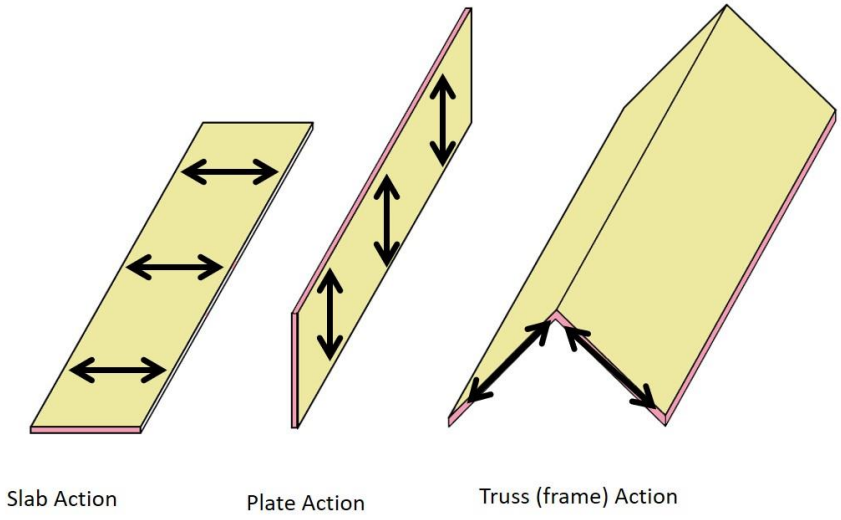


Figure 15 : the actions on folded plates

In the folds, if you see a fold, the folds are actually having either a slab action or maybe a plate action or maybe a truss action which I have described in the Figure-15.

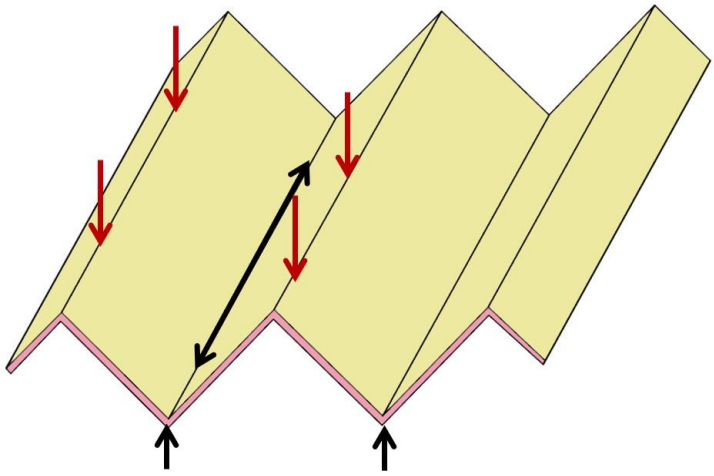


Figure 16 : the typical load path of a folded plate

So, in the folds where there are truss actions, what happens is that at first the external forces which is shown in red color arrows in Figure-16, will generate the membrane force, which as we have discussed in membrane structure. The flow of the forces will generate the truss action on the inclined plate and finally if you see those trust actions membrane forces are given in the blue color arrows. Then finally from such plates those forces are accumulated in the lower most point lower most point of the junctions and the black color arrows are generated, the forces are generated and

finally they transmit the load to the structure. So, this is the typical load path of the folded plate. The load path has been shared by the different plates and finally to the columns.

When we see the types of folded plates, there are three main types.

i. Folded Plate Surfaces
ii. Folded Plate Frames
iii. Spatial Folded Plate Structures

Folded Plate Surfaces:

So, this is the folded plate surfaces where it is only the roof surface or may be only typical one surface is created by the folded plate, which is very common in case of any kind of industrial structure may be a kind of a the bus stand or maybe sometimes in the railway stations also. In this Figure-17 you can see that a roof has been generated by a triangular folded plate. If you see the other surfaces like the other walls and all they are completely like straight forward walls.

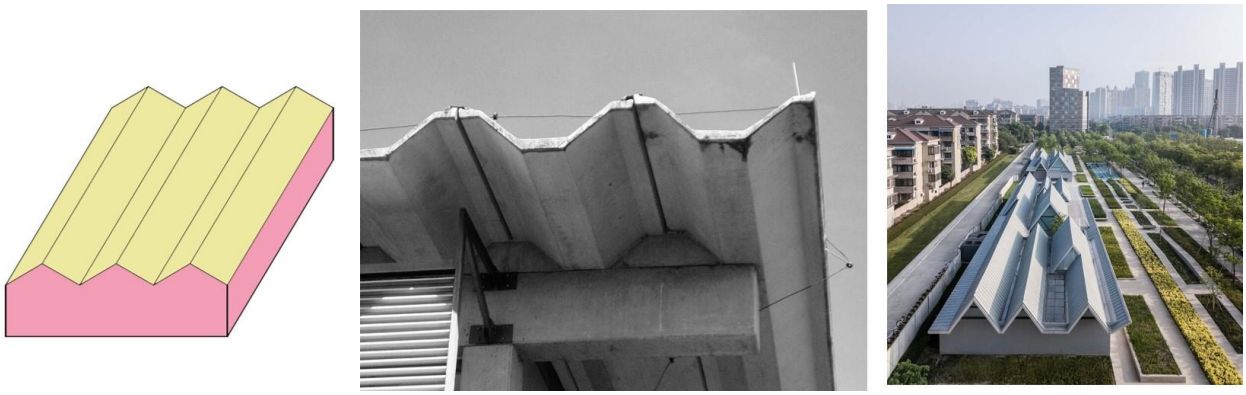


Figure 17 : the folded plate surfaces

Folded Plate Frames:

Folded Plate Frame structures are formed by combining different shapes of plates in three planes to represent a series of structural portal.

where there is not only the roof but also a frame that is the side members; the columns or maybe the wall members are also generated with the folded plate. The geometry of the roof, the geometry of the walls are clubbed together as a monolithic construction. The Figure-18 suggests that, the top roof structure and the wall structure comes under the different folds having an integrated geometrical pattern and this photograph is also of that type. The folded plates act as a wall and the continuous folded plates also act as a roof.

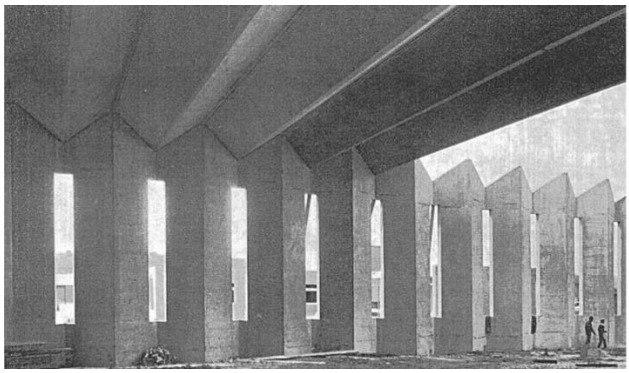
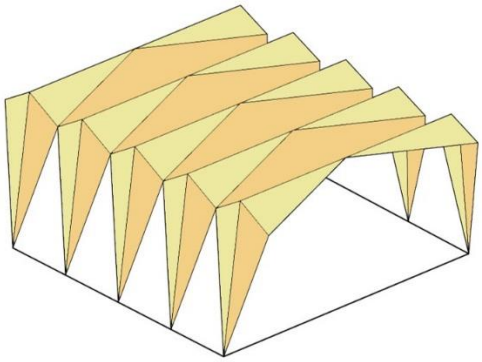



Figure 18 : folded plate frames

Spatial Folded Plate Structures:

Spatial Folded Plate Structures are formed by combining different shapes of plates in various orientation to create a spatial form.

Here, it is designed with total space or total volumetric point of view a folded plate has been designed. So, this particular Figure-19 is showing that so you can have a geometrical shape which comes from the surface development of typical solid and we can use the different folds as a kind of roof and also merging to the wall.



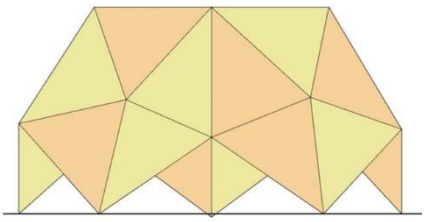


Figure 19 : Spatial Folded Plate Structures

If we see the application of the folded plate, it is most commonly used in:

- Industries
- Stadiums
- Airports
- Auditoriums
- Hotels

Now, let us go to some of the applications. The first example is the Delft Polytechnic, Netherland. If you see the section view, as shown in Figure-20, its roof is made of typical folded plate resulting to very high thickness. Here it needs a large span without columns. So, it has only in the peripheral area where we can have the columns. But interestingly this particular auditorium is lifted from the original ground level, and hence it is a race floor; and the raised floor is under action of a cantilever beam merging out from the respective 2 or 4 columns in the four typical point.

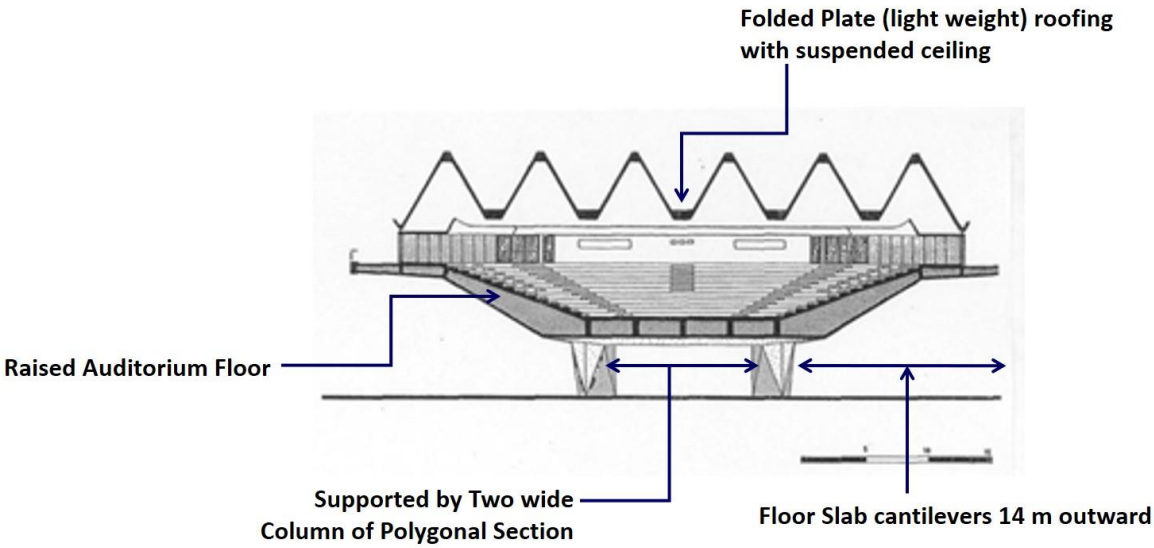


Figure 20 : Delft Polytechnic, Netherland

The 2 columns which are actually taking the cantilever box beam is also connected to each other by a box structure. So, what we have discussed in the earlier presentation is that the balancing moment or balancing kind of a structural system is also present over here.

The next example is a sports center of the Switzerland, where the folded plate is acting as a wall also and also for the roof.

Figure 21 : The Sports Centre, Mulimatt, Switzerland

Another example is of United States, Air Force Academy Chapel, where an overall space, whole space is designed as a folded plate and those plates are interestingly designed. It is designed such a way that there are some typical triangular openings and those openings are generated by virtue of the different folded plate actions or the geometrical placement of the folded plate. Those openings are finally dealt with the glass and those allows the natural light source.

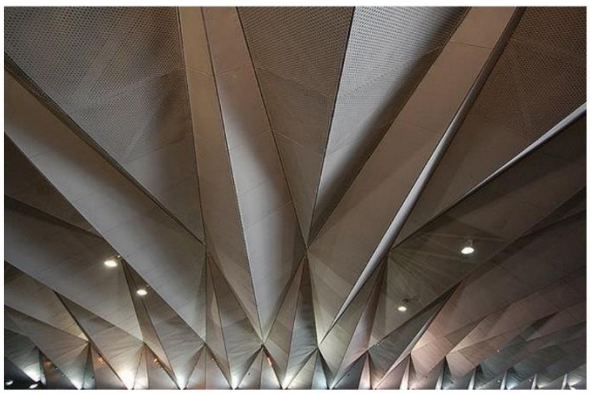
Figure 22 : The United States Air Force Academy Chapel in Colorado, USA

The next example is of an airport. As I told you folded plates have applications in airports also This is an airport from Russia, with mega columns. The columns are very huge and white cross-sections are supporting the folded plate in and the folded plate is acting as a roof structure.

Figure 23 : Pullkovo Airport, Russia

So, this is Yokohama International Passenger Terminal, where a three-dimensional folded plate has been used and the next one is the Sardar Vallabhbhai Patel Stadium, Ahmedabad this is also

very interesting. The seating gallery is camouflaged with the inclined folded plates and those ribs if you see minutely observe, the ribs actually acts as column but it is designed as folded with plates.



Osanbashi Yokohama International Passenger Terminal, Japan

Sardar Vallabhbhai Patel Stadium, Ahmedabad

Figure 24 : the folded plate structure

So, these are the reference of this particular lecture:

- **Structure Systems** by Heino Enge, Hatje Cantz Publisher
- **Structure and Architecture** by Meta Angus J. Macdonald, Elsevier Publication
- **The Structural Basis of Architecture by** Bjørn N. Sandaker, Arne P. Eggen, Mark R. Cruvellier, Routledge
- **Building Structure Illustrated** by Francis D.K. Ching, Willy

Thereby in conclusion I must say that:

Waffle Slab and Folded Plates are two unique types of plate structure. The load distribution and transmission depend on the close association of beam and slab. It can be used as long span structural system.

So, in the next lecture we will go to the module number eight and that will be our last module. In that we will deal with the spatial structures.

Thank you very much.