ISSN 1019-1011

Ç.Ü.MÜH.MİM.FAK.DERGİSİ		Haziran	2004	Ç.Ü.J.FAC.ENG.ARCH.	
CİLT.19	*SAYI.1*	*June*		*VOL.19*	*NO.1*

SUSCEPTIBILITY OF DOUBLE-LAYER GRID STRUCTURES TO PROGRESSIVE COLLAPSE

Hakan T. TÜRKER
M.K.U., Department of Civil Engineering, Hatay/Turkey
Celal KÖSTEM
Lehigh University, Department of Civil and Environmental Engineering, Bethlehem, PA
Orhan AKSOGAN
Ç.U., Department of Civil Engineering, Adana/Turkey

ABSTRACT : *Because of their large internal degree of static indeterminacy, double-layer grid (DLG) structures are often assumed to have sufficient redundancy such that the loss of one member would cause force redistribution that can be accommodated by remaining structures. However, results of the several experimental and parametric studies show that progressive collapse could occur following the loss of one of several potentially critical members when the structures are subject to full service loading. This paper presents the susceptibility of DLG structures to progressive collapse when any one of a number of critical members has lost its load carrying capacity. By changing the parameters, it is aimed to determine which structure parameters improve the ability of the damaged structure to avoid complete failure.*

ÇİFT TABAKALI GRID YAPILARIN ZİNCİRLEME ÇÖKÜŞE KARŞI HASSASİYETLERİ

ÖZET : *Çift tabakalı grid (ÇTG) yapıların yüksek derecede hiper statik olmaları nedeniyle, herhangi bir elemanını kaybetmeleri durumunda, kaybolan elemanın yükünün diğer elemanlara dağıtılmak suretiyle yeterli güvenlikte oldukları düşünülür. Yapılan deneysel ve parametrik çalışmalar, bu yaygın görüşün aksine, çöken kritik elemanın diğer elemanların zincirleme çöküşüne neden olabileceğini göstermiştir. Bu makalede çift tabakalı grid yapıların herhangi bir neden sonucu kritik elemanlarından birini kaybetmeleri durumunda, zincirleme çöküşe karşı hassasiyeti incelenmiştir. Değişik parametreler irdelenerek, ÇTG yapıların zincirleme çöküşüne karşı güvenliğini arttıran parametreler belirlenmiştir.*

1. INTRODUCTION

DLG structures consist of two plane grids forming the top and bottom layer, parallel to each other and interconnected by diagonal members (see Figure 1). These kinds of structures are becoming increasingly popular for providing large column free areas. DLG structures are considered to be efficient systems, with large stiffness to weight ratios, and it is also aesthetically pleasing (5, 6).

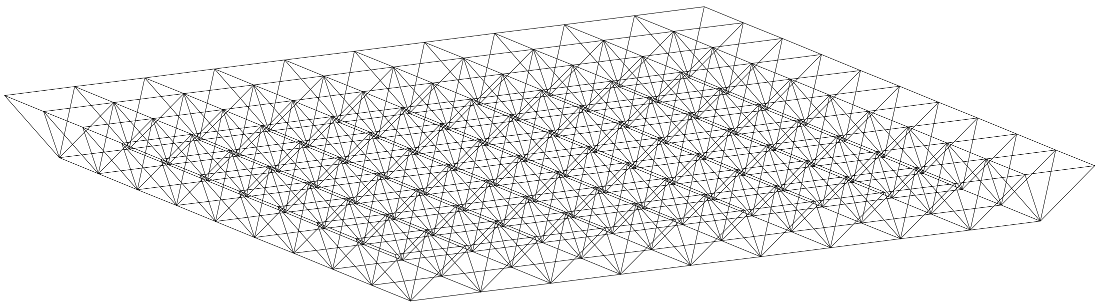


Figure 1. Three dimensional view of double layer grid

Because of their large internal degree of static indeterminacy, DLG structures are often assumed to have sufficient redundancy such that the loss of one member would cause force redistribution that can be accommodated by remaining structures. However, results of several experimental and parametric studies show that progressive collapse could occur following the loss of one of several potentially critical members when the structures are subject to full service loading (4). Progressive collapse has been defined as "the widespread propagation of failure following damage to a relatively small portion of the structure" (1). There may exist substantial discrepancies between the structural behavior as predicted by the analytical model and the actual behavior (4). Extensive experimental evidence indicates that double-layer grids are highly sensitive to effects of random imperfections, owing to their high degree of static indeterminacy and stiffness. Load bearing capacity of these structures often falls 25% to 40% below the elastic limit (4, 10, 11).

There are many events that can cause the failure of a structural member. The important question is how the structure would behave after the loss of the member. This paper presents the susceptibility of DLG structures to progressive collapse when any one of a number of critical members has lost its load carrying capacity. By changing the parameters, it is aimed to determine which structure parameters improve the ability of the damaged structure to avoid complete failure.

1.1.Space Truss Behavior

Space truss behavior is the result of its configuration; the interaction of its configuration, the interaction of its many members and joints, its supports, and the external loading it is required to sustain.

The parameters influencing the effect of an individual member on the truss behavior include its initial curvature, yield strength of material, residual stresses resulting from its manufacture and fabrication, load eccentricities, and finally, the nature of the force-tension or compression- in the member.

1.1.1 Member Behavior

There are two physical phenomena, which control the upper bound of the capacity of a member axially loaded in compression. First, there is yielding due to the material behavior which includes the ductility of the material as well as the strength of the material. In this case, the maximum load capacity, (see **Figure 2**) would be a function of the material properties and the cross-sectional properties. Thus,

$$P_{\max} = P_y = \sigma_y A$$

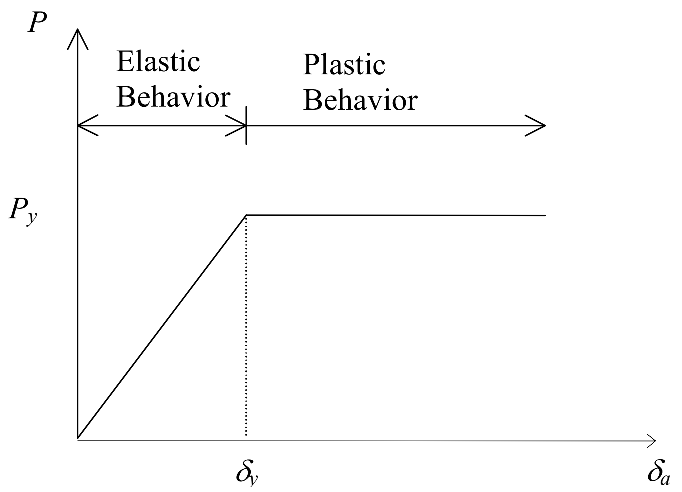


Figure 2. Yielding controls P vs δ_a

The second phenomenon is buckling. This is sudden lateral movement at the center of compression member while the ends remain axially in line. The Euler buckling load of a compression member is a function of the length of the member as well as the cross-sectional and material properties. Thus,

$$P_{\max.} = P_E = \frac{\pi^2 EI}{L^2}$$

Referring to
Figure 3 it can be seen that the behavior of the buckling phenomenon can be presented in two different manners.
Figure 3(a) is a plot of axial compressive load, P, versus the axial shortening, δ_a, while
Figure 3(b) is a plot of axial compressive load, P, versus the lateral deflection, δ_L, measured at the mid-point of the length.

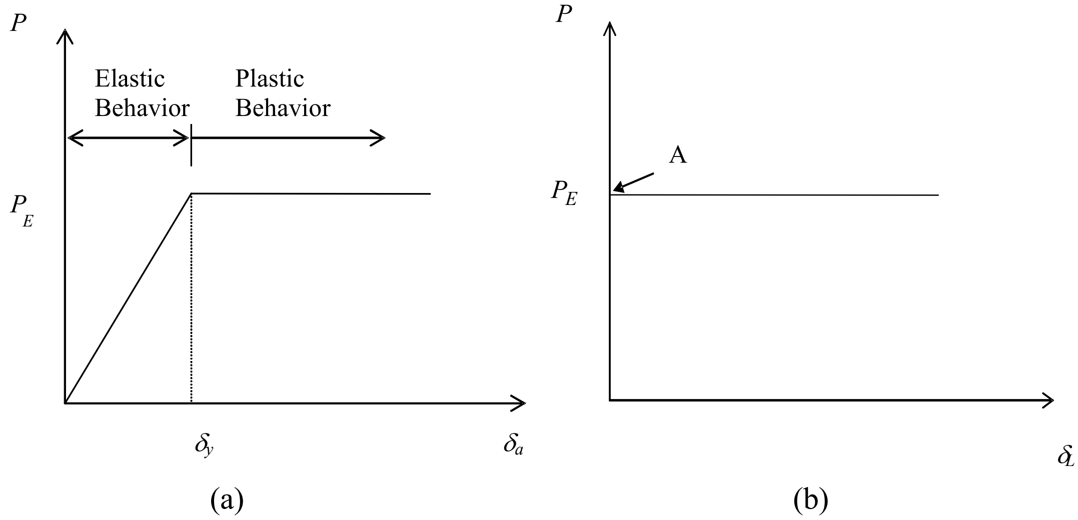


Figure 3. Buckling Controls (a) P vs δ_a (b) P vs δ_L

Point A
Figure 3(b) has been noted as a bifurcation point because, theoretically, the member can remain straight or displace laterally under the same load. Prior to reaching the bifurcation point the member remains absolutely straight with increasing load. Once the bifurcation point, or the Euler load, is reached the member can displace laterally by an indeterminate amount.
Figure 2, showing the yielding phenomenon,
Figure 3(a), showing the buckling phenomenon, present the same member behavior when considering the axial load versus the axial displacement. The slope of the curve prior to the maximum load is a material property, known as the elastic modulu, E, which is a constant for a particular material. Whether the buckling phenomenon is obtained before the yielding phenomenon is function of the length of the member.

Referring to the plot of the maximum compressive axial load, P_{max}, versus the slenderness ratio, L/r, in **Figure 4**, it can be seen that the Euler buckling phenomenon controls at slenderness ratios greater than that at which the Euler load is equal to the yield load, $(L/r)_t$. The yielding phenomenon controls at slenderness ratios below $(L/r)_t$.

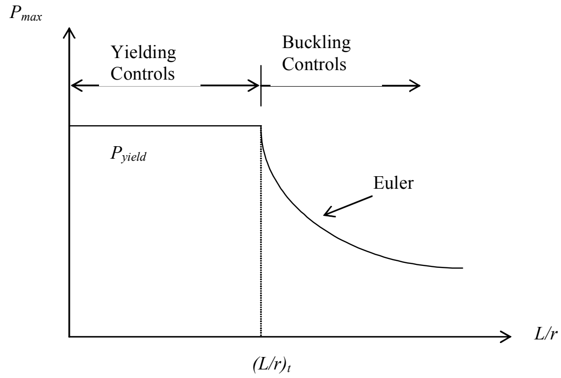


Figure 4. P_{max} vs (L/r)

2. PARAMETRIC STUDY

The parameters to be investigated in this study were chosen as span to depth ratio, support conditions, number of supports, and span to module size ratio. The span to depth ratio had values of 7, 10, 14, 17.5, 20, 25.45, and 35. The ratio of the number of modules per span had values of 7 X 7, 10 X 10, and 13 X 13. Span is defined in this research as the distance between columns in x or y direction.

All combinations were analyzed using linear analysis methods. The damaged truss structures were analyzed using alternate path method (2, 3, and 7). Various members were individually removed from each truss and the member factors of safety calculated. The member factor of safety is defined as the ratio of the ultimate capacity of the member to actual member force. Failure is defined as factor of safety less than one.

Six models of double-layer grid structures were chosen for parametric study in this research. The plan and side elevation are shown in **Figure 5**. These structures cover an area of 21 m by 21 m. The space frame is an example of DLG of the square-on-square type. All of these models were designed under the same uniform load conditions and analyzed. SODA (13), which is a linear analysis program, was used for designing and analyzing the models. All the analyses are conducted for space trusses. Only active degrees of freedom (DOF), except supports, are the three translations. The prototypes were designed with two support conditions, which are pin support and simple support. Pin support is defined in this research as one for which translations in all directions are prevented. Simple support is defined, see **Figure 6**, as a node (node 1) of structure for which all translations as well as rotations are prevented. The nodes along the x and y directions (node 2 & node 3) such that all rotations and the translations other than that in the direction of the axis it lies on are prevented. The support node (node 4) can move only in x and y directions and not in z direction. Steel circular hollow sections have been used for the members of the structures. Members in these prototypes were assumed to be pin-ended and selected from 37 different circular hollow sections, which are contained in SODA (13). The AISC (12) specifications (AISC-LRFD-93) were used in the member selection.

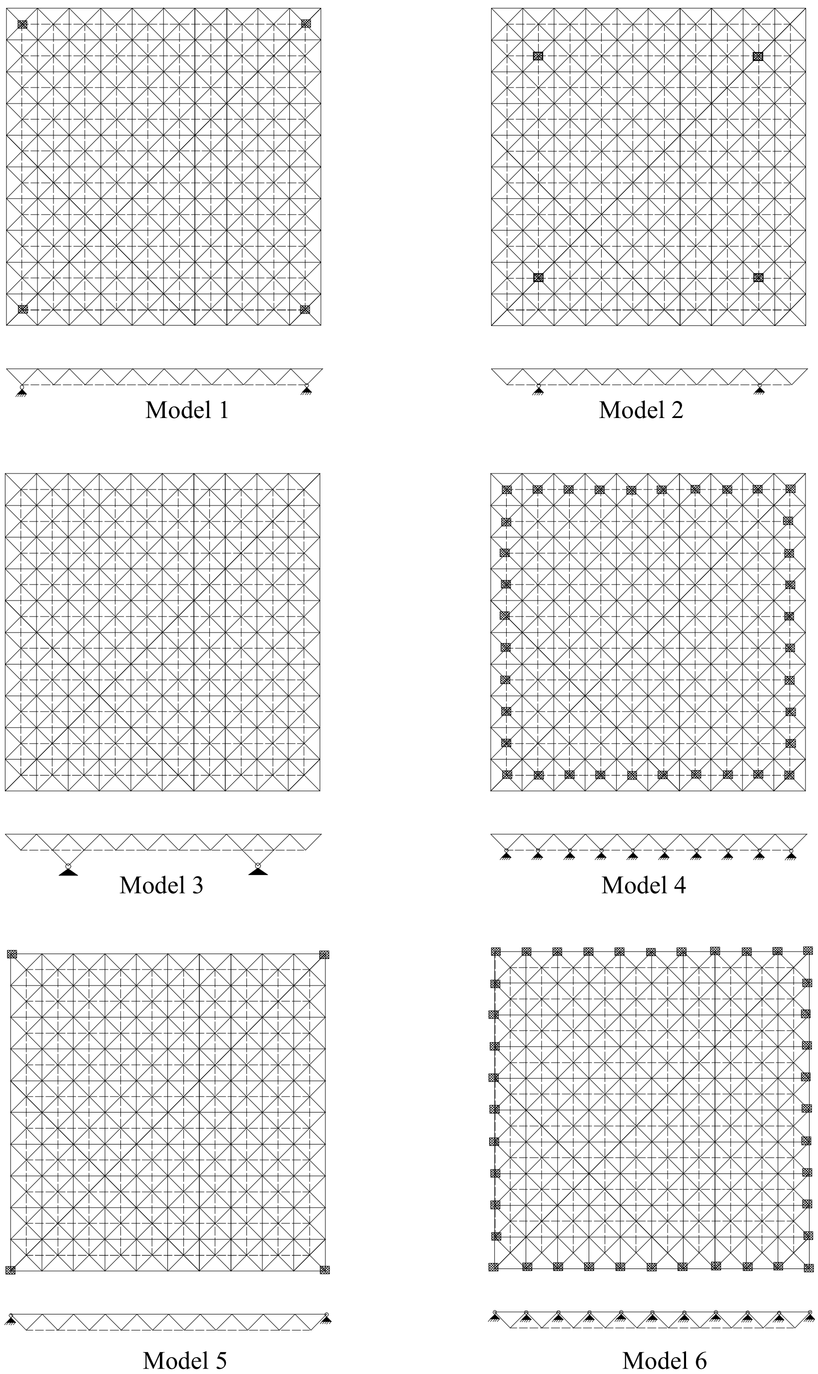


Figure 5. Models used for parametric study

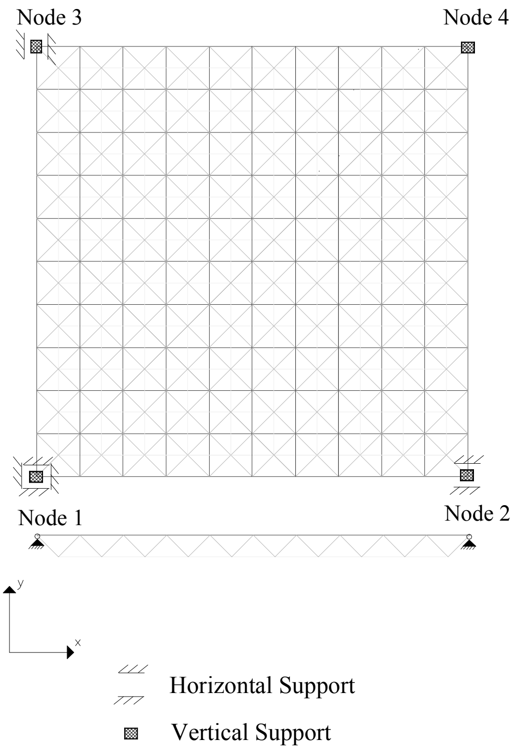


Figure 6. Simple Support Definition

2.1. Alternate Path Analyses

The alternate path analysis method was utilized in order to analyze the behavior of the DLG structures subject to loss of a critical member. The damaging event is considered unknown and for this investigation the damaged member was assumed to have zero capacity. One important aspect to note is that this method is independent of actual event which caused the damage. Regardless of the damaging event, the structure must demonstrate the ability to redistribute the loads in such a way that the structure is able to maintain acceptable levels of safety.

For our alternate path analysis, the initial damage is simulated by simply removing one of the critical structural members. Then the structure was analyzed under the design load combination. Each time one of the critical members was removed. Then, it was examined if the removing causes other members to fail in the structure. Failed member is defined in this research as a member whose actual force exceeds its allowable force. SODA (13) determines failed member, which violate AISC (12) rule, according to AISC. For the removed members, the young module was assumed as zero in SODA (13).

For each model to be investigated, a large number of members were chosen for removal in a certain pattern. The members chosen for removal are selected in the area of expected vulnerability. It is important to note that the DLG structures were analyzed subject to the loss of only a single member at any given time.

3. DISCUSSION OF THE RESULTS OF THE PARAMETRIC STUDY

3.1. Corner Support Model Analyses Results

The focus of this section is the evaluation of the exterior and interior corner supported DLG models and their behavior when subjected to the loss of a single member. When creating the models to be analyzed, the base model defined previously was varied for the parametric study of susceptibility to progressive collapse. A total of eighteen models were used to obtain the results presented in this section.

3.1.1. Exterior and Interior Support

The truss models were analyzed to determine if the location of the support had an effect on the susceptibility of the structures to progressive collapse. In **Table 1** and **Table 2**, the results of this investigation are presented.

Table 1. Number of Failed Members

# Modules	Pin Support		Simple Support	
	Exterior Support Model-5	Interior Support Model-1	Exterior Support Model-5	Interior Support Model-1
7 X 7	160	10	153	12
10 X 10	299	10	284	15
13 X13	401	5	386	8
Span :21 m by 21 m, Depth : 1 m				

Table 2. Percentage of Failed Members

# Modules	Pin Support		Simple Support	
	Exterior Support Model-5	Interior Support Model-1	Exterior Support Model-5	Interior Support Model-1
7 X 7	39.4%	2.5%	38.1%	3.0%
10 X 10	37.7%	1.3%	35.5%	1.9%
13 X13	29.6%	0.4%	28.5%	0.6%
Span :21 m by 21 m, Depth : 1 m				

Table 1 shows the number of members which failed due to the loss of a solitary member in the single worst case analyzed. From Table 1, it can be seen that the interior support models sustain much fewer failed members than exterior support models do. One factor that increased the performance of the interior support models is the shorter unsupported span. Another factor could be the difference in critical members between the two support types. The most critical members for all the exterior corner models analyzed were the corner diagonal from the point of support to the corner of the lower chords. The loss of this member reduced the capacity of the structure and compelled the truss to support the load in the span diagonally across the structure, effectively increasing the unsupported length of the truss.

The most critical members for the interior support models were the central chord members along the perimeter of the structure. These members were also found to be critical for the exterior support models but they are not as critical as the corner diagonal discussed previously. The top and bottom members along the perimeter carry a large portion of the load in a corner supported double-layer grid structure. If one of these members is lost, the next member in the perimeter must support the load carried by the lost member.

3.1.2. Effect of the Number of Modules per Span

Even though the span lengths of all corner support models analyzed were kept constant at 21 m, the number of modules per span was analyzed using three values. They are 7 modules per span, 10 modules per span, and 13 modules per span. The results of this analysis can be seen in Table 1 and Table 2 which have been previously shown. Depending on how the results are interpreted, different conclusions can be drawn. If the results are examined in terms of the number of failed members which is due to the loss of a single member, there appears to be a trend of increased number of failed members as the number of modules per span increases. Another way to investigate the results would be in terms of the percentage of members which fail due to the loss of a single member. Even though the number of members damaged in the lower number of module DLG structure was less, the percentage of DLG damaged members was greater. With a greater percentage of the structure remaining intact after a damaging event, there is greater opportunity for the structure to find an alternate path for the load and avoid a complete failure. Therefore, as the number of modules increases, the chance of the survival of the structure may also increase.

3.1.3. Effect of Span to Depth Ratio

In order to investigate the effect of varying the span to depth ratio on the susceptibility of the double-layer grid structures to progressive collapse, eight corners supported models were created and analyzed using the SODA computer program. The results of these tests are presented in Table 3. Inspecting Table 3, no clear trends or conclusions can be drawn concerning the effects of the span to depth ratio.

Table 3. Model-5 Number of Failed Members

Module #	Depth [m] Span to Depth Ratio						
	d=10 7	d=7 10	d=5 14	d=4 17.5	d=3.5 20	d=2.75 25.45	d=2 35
10 X 10	228	235	334	307	299	301	248

3.2. Perimeter Support Analysis Results

Two types of perimeter support models are compared here. One of them is exterior support at the truss upper nodes (model-6, see figure 5). The other is interior support at the truss lower nodes (Model- 4, see figure 5). Each of these models was a square configuration with the same number of modules in x and y directions. They were designed under the same load conditions and analyzed. When creating the models to be analyzed, the base model defined previously was varied such that each parameter for parametric study. A total of eighteen models were used to obtain the results presented in this section.

3.2.1. Exterior Support and Interior Support

One of the conditions to be varied for compression purposes was the location of support. The results of the tests have been tabulated in Table 4 and Table 5. Numerous members were removed individually from each model. Of all individual members removed, the worst case was the one which produced the greatest number of failed members. The most critical member for each different group (Diagonal, upper, lower members) was removed. The numbers of failed members after the removal of the most critical members were tabulated in Table 4. In Table 4 the numbers of failed truss members for the worst single test case of each model are presented. Table 5 shows the percentage of the failed truss members.

Table 4. Number of Failed Members

# Modules	Pin Support		Simple Support	
	Exterior Support Model-5	Interior Support Model-1	Exterior Support Model-5	Interior Support Model-1
7 X 7	3	-	3	1
10 X 10	3	-	3	1
13 X13	4	-	4	-
Span :21 m by 21 m, Depth : 1 m				

Table 5. Percentage of failed members

# Modules	Pin Support		Simple Support	
	Exterior Support Model-5	Interior Support Model-1	Exterior Support Model-5	Interior Support Model-1
7 X 7	0.80%	-	0.80%	0.25%
10 X 10	0.38%	-	0.38%	0.13%
13 X13	0.29%	-	0.29%	-
Span :21 m by 21 m, Depth : 1 m				

As it can be seen from the above tables, the interior perimeter support cases sustain fewer failed members after the removal of the most critical member than the exterior support cases.

3.2.2. Effect of Span to Depth Ratio

Investigations of the effect of depth on the susceptibility of double-layer grid structures to progressive collapse involved the same 21 m span models used previously (10 X 10), but with span to depth ratios varying from 7 to 35. The results of the single worst case from these tests are shown in Table 6. No clear trends are observed in these results.

Table 6. Number of Failed Members Model-6

Module #	Depth [m] Span to Depth Ratio						
	d=10 7	d=7 10	d=5 14	d=4 17.5	d=3.5 20	d=2.75 25.45	d=2 35
10 X 10	2	6	3	9	3	3	2

3.2.3. Effect of Number of Modules per Span

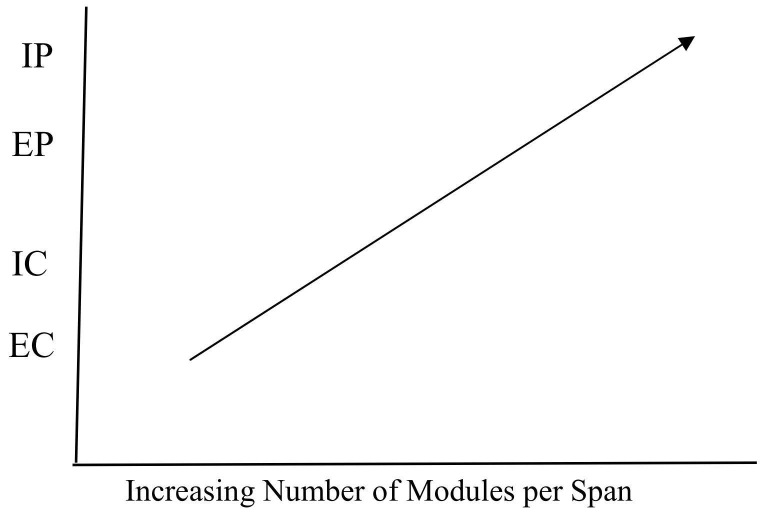
Holding overall span length constant at 21 m, the number of modules per span was analyzed with three values: 7 modules per span, 10 modules per span, and 13 modules per span. In order to determine the effect of the number of modules to susceptibility of DLG to progressive collapse, it is necessary to refer to Table 4 and Table 5 again. The number of failed members for each case shows that the results are roughly equivalent and may lead to believe that the effect of varying the number of modules is negligible. If the results are viewed in terms of percentage of the truss which fails, the conclusion is different. As the number of modules per span is reduced, there is an increase in the percentage of failing members. Both the exterior and the interior support conditions show the same trend. If a smaller percentage of structure has exceeded its capacity, there is a higher probability that the structure would be able to find an alternate path for redistribution of the load. If there are a greater number of members per a given area, the structure can distribute the overload to more members. Therefore, the higher the number of modules per span, the lower the susceptibility to progressive collapse.

3.3. Perimeter Support -- Corner Support

Inspecting the tables in the section above, it can be seen that the perimeter support models sustained significantly fewer damaged members due to loss of a member of DLG. One reason for the difference in the damage levels is the difference in the fundamental behavior between the two support types. The corner support models transfer the load to the outer members and then the supports. Consequently, these members are the most critical group and their loss cause the greatest damage. As the perimeter support models transfer the load towards the outside of DLG, the load is carried by the continuous supports. The critical members for the perimeter support models are the members in the central portion of the structure.

3.4. Finding of Parametric study on Susceptibility of Double-layer Grid Structure to Progressive Collapse

As stated previously, the main purpose of this paper is to examine and identify the influence of particular parameters on the susceptibility of DLG structures to progressive collapse. The susceptibility of a structure to progressive collapse is defined as the level of risk that the structure would fail as a result of the damage to a small portion of it. Table 7 and Figure 7 summarize the results. Figure 7 does not contain the effects of depth because they were found to be insignificant in the test results. In Figure 7, as the structure moves from exterior corner support with few modules per span to a structure with interior perimeter support with a larger number of modules per span, the susceptibility of the structure to progressive collapse decreases. In this research, decrease in susceptibility is defined as a reduction in the number of members which have a factor of safety less than one after the removal of a member from the structure.



EC : Exterior corner supported structure

IC : Interior corner supported structure

EP : Exterior perimeter supported structure

IP : Interior perimeter supported structure

Figure 7. Resistance to progressive collapse

Table 7. Summary of parameter effects on susceptibility of DLG to progressive collapse

Variable	Effect on Susceptibility
# Modules	Moderate effect
Depth	no effect
Support Condition	Significant effect

4. REFERENCES

1. Makowski,Z.S. "Analysis, Design and Construction of Double-Layer Grids", John Wiley & Sons, New York, New York, 1981.

2. Makowski,Z.S. "Modern Space Structures and Their Impact on Contemporary Architecture", Short Course of Lectures at Cukurova University, Adana, Turkey, 18 th May, 1993.

3. Hanaor, Ariel "Snags and Solutions in Double-Layer Grid Design", Building Structures Congress `87,Sherman, D.R., ed., ASCE, New York, 319-331,1987

4. Breen,J.E. "Summary of Report of Research Workshop on Progressive Collapse of Building Structures", University of Texas at Austin, Austin, TX, 1975.

5. Schmidt, Lewis C., Morgan, and Clarkson, John A.," Space Trusses with Brittle-Type Strut Buckling", Journal of Structural Division, Vol. 102, pp. 1479-1492, No. ST7, 1976.

6. Schmidt, Lewis C., Morgan, Peter R. and Hanaor Ariel, " Ultimate Load Testing of Space Trusses", Journal of Structural Division, Vol.108, pp. 1324-1335, No.ST6, 1982.

7. Ellingwood,B. and Leyendecker,E.V. "Approaches for Design Against Progressive Collapse", Journal of the Structure Division, ASCE, Vol. 104, 1978.

8. Ellingwood,B., Leyendecker,E.V and Yao,J. "Probability of Failure from Abnormal Load", Journal of Structural Engineering, Vol. 109, No.4, April, 1983.

9. Murtha-Smith, Erling. "Alternate Path Analysis of Space Trusses for Progressive Collapse", Journal of Structural Engineering, ASCE, Vol. 114, No. 9, 1988.

10. SODA Structural Optimization Design and Analysis, A Structural Analysis and Design Program for Static response of Linear Systems, Acronym Software Inc.

11. AISC Steel Construction Manual, Second Edition, American Institute of Steel Construction, 1994.