# Optimum Shape in Brick Masonry Arches Under Static And Dynamic Loads

KAVEH KUMARCI, ARASH ZIAIE, MEHRAN KOOHIKAMALI, ARASH KYIOUMARSI

***Abstract*** - The objective of this study is to determine brick masonry arches under dynamic and static loads. In this paper, considerable attention is given to arches, their importance, modeling stages, dynamic analysis, static analysis and arch optimization using ANSYS11 software. A multiple stage analysis framework was conducted for semicircular arch:

1- The study of optimum shape for semicircular arch on the base of minimize of arch weight.
2- Determination of linear and nonlinear analysis limits by increase of density.
3- The study of optimum shape in semicircular arch by linear and nonlinear analysis.

All of these stages have been conducted for obtuse angel arches, four- centered pointed arch, tudor arch, ogee arch, equilateral arch, catenary arch, lancet arch, four-centered arch (normal, diminished and steep). The main purpose has been study of arch optimum shape for minimize of weight: Finally, according to the results, the optimum shape in arches under dynamic load has been determined.

***Keywords-*** *optimum shape- arch- dynamic load- linear and non linear analysis- tensile stress*

## I. INTRODUCTION

BEFORE, arch was defined as a part of circle or bow. If we want to define it, we can say it is a curve surface for covering, that it's span is higher than it's depth .Overall, arches are classified to three groups:

1- circular arches and similar to that
2- obtuse angle arches
3- decorative arches

Time dynamic analysis is an analytical method to determine responses in each time section, especially for earthquake that a structure is under accelerations of earth motion (accelerograph) in the base level. In this model, structure dynamic response is function of time and calculated by number integral in equation of structure motion. [1,10,14,15, 16]

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## II. MODELING, ANALYSIS AND OPTIMIZATION OF ARCH SHAPE

Arch modeling has been conducted by ANSYS11 software. Also dynamic analysis has been conducted by north-south horizontal accelerations of Elcentro earthquake in 1940.In this earthquake the time, maximum acceleration, maximum velocity and maximum displacement were 31.98 sec, 0.31g, 33 cm/sec and 21.4cm, respectively. The element which used in this analysis was SOLID 65. Arch shape optimization emphasized on the minimizing of arch weight. So, the base and top thickness, maximum tensile stress and weight of structure have been defined as design variable, state variable and objective function, respectively Optimization has been conducted in Design Optimum Processing. [5,6,8,10]

### A. Geometrical Modeling:

According to optimization of design variables, such as base thickness (t0) and top thickness (t1) as parameters, all of key points are defined as follow. [9]

In order to study of this material, semicircular arch is defined by key points as parameters (fig.I).

Point 1: (0, 0) Point (2): (R, 0) Point3: (-R, 0) Pint4: (0, R)
Point 5(R+t0, 0) Point6: (-R-t0, 0) Point 7: (0, R+t1)

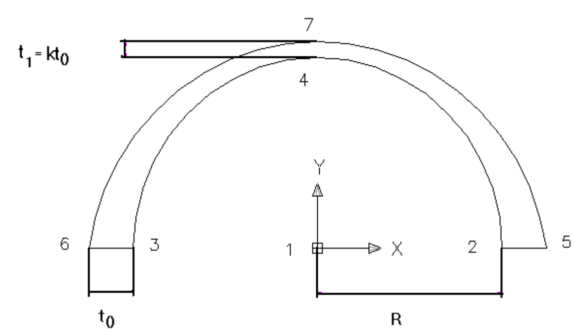



fig1: semicircular arch

In arch modeling, the tolerance increases because the thickness decreases from base to top. We should remember that in modeled arch, the thickness decrease from base (t0) to top (t1) linearly. Also, arch thickness in direction of length axis is 20 cm. The motion of support nodes is zero, and dynamic force has no effect on them. Also, brick masonry is made by brick and mortar as homogenous material (table I). The efficient factors in inelastic nonlinear analysis show in (table II). [4,7,12]

Table I: Brick masonry specification

| | |
|---|---|
| density( $\rho$ ) $kg/m^3$ | 1460 [2] |
| Elastic modulus $N/m^2$ | $5\times10^8$ [3] |
| Allowable tension stress($f_t$) $N/m^2$ | $0.5\times10^5$ [2,3,4] |
| Poisson ratio ( $\upsilon$ ) | 0.17[4] |

Table II: Effective coefficient in non elastic and nonlinear analysis

| | |
|---|---|
| motion coefficient for open crack | 0.1 [5] |
| motion coefficient for close crack | 0.9 [5] |
| allowable tension stress $N/m^2$ ($f_t$) | $5\times10^4$ [2,3,4] |
| allowable compressive stress $N/m^2$ ($f_c$) | $5\times10^5$ [2,3,4] |

## III. EVALUATION OF OPTIMUM SHAPE IN SEMICIRCULAR ARCH

The analysis conducted for semicircular arch in five spans: 4,5,6,7 and meters (TableIII,Table IV,Fig II).

TableIII: specification of optimum shape for semicircular arch with various spans under dynamic load.

| *Span Length* | *4(m)* | *5(m)* | *6(m)* | *7(m)* | *8(m)* |
|---|---|---|---|---|---|
| $t_0(m)$ | .8328 | .973 | 1.2154 | 1.4828 | 1.6208 |
| $t_1(m)$ | .2763 | .28182 | .297 | .31879 | .36388 |
| *k* | .3317 | .2896 | .2443 | .2149 | .2245 |
| $t_0/R$ | .4164 | .3892 | .4051 | .4236 | .4052 |
| $t_1/R$ | .1381 | .1127 | .099 | .091 | .0909 |
| $\overline{W}/H$ | .4347 | .917 | 5.68 | .435 | .8064 |
| $N/m^2$ $(\sigma_t)_{max}$ | 50982 | 48072 | 52815 | 51600 | 48430 |

TableIV: specification of optimum shape for semicircular arch with various spans under static load.

| *Span Length* | *4(m)* | *5(m)* | *6(m)* | *7(m)* | *8(m)* |
|---|---|---|---|---|---|
| $t_0$(m) | .5829 | .681 | .85 | 1.037 | 1.62 |
| $t_1$(m) | .2486 | .2531 | .2673 | .2869 | .3638 |
| k | .423 | .3716 | .3144 | .2766 | .2245 |
| $t_0$/R | .29 | .27 | .283 | .2962 | .4052 |
| $t_1$/R | .12 | .101 | .099 | .082 | .0909 |
| $\overline{W}/H$ | 4 | 4 | 5.68 | 4 | .8064 |
| $(\sigma_t)_{max}$ $N/m^2$ | 50326 | 50982 | 52815 | 51100 | 48430 |

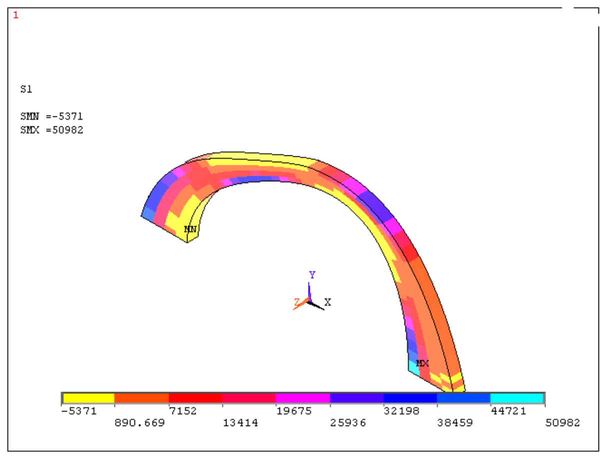



Fig II: semicircular arch modeling by ansys

## IV. EVALUATION OF DIFFERENT ARCH AND THEIR OPTIMUM SHAPE

Here, in addition to semicircular arch, the obtuse angel, four centered pointed, tudor ogee arch, equilateral catenary, four centered, lanced arches have been studied. Analyzed arches were studied in three spans: 4, 5 and 6 meters. In each span, dynamic force, maximum tension stress, arch optimum dimensions and stability factor are calculated. Also, Obtus angel, four centered pointed tudor and ogee arch, arches have been analyzed in 3 levels: normal, diminished and steep (Table V-XI, Fig III-XI ). [1,2,3,8,9]

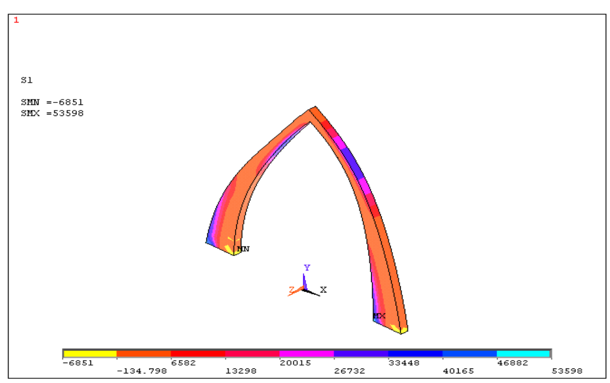



Fig III: Catenary arch modeling by ansys

Table V: Comparison of optimum arches under dynamic load

| L(m) | | | $t_0(m)$ | $t_1(m)$ | $K$ | $\overline{W}/H$ | $(\sigma_t)_{ma}$ |
|---|---|---|---|---|---|---|---|
| Catenary arch | | 4 | .8969 | .21984 | .2451 | .464 | 47907 |
| | | 5 | .99269 | .27688 | .2789 | .872 | 45231 |
| | | 6 | 1.1539 | .28849 | .2500 | 2.54 | 47095 |
| Lancet arch | | 4 | .96243 | .18058 | .1876 | .4 | 53598. |
| | | 5 | 1.06 | .2095 | .197 | .7842 | 46291 |
| | | 6 | 1.132 | .2843 | .214 | .492 | 50765 |
| Ogee arch | diminished | 4 | .83438 | .39919 | .4784 | *.41* | *49629* |
| | | 5 | .81818 | .34175 | .4176 | .661 | 46588 |
| | | 6 | .80817 | .24095 | .2981 | 2.35 | 46681 |
| | normal | 4 | .81414 | .19308 | .237 | 3.44 | 53685 |
| | | 5 | .8389 | .22744 | .2711 | .557 | 50578 |
| | | 6 | .98287 | .36179 | .3680 | 1.145 | 53037 |
| | steep | 4 | 1.3931 | .3143 | .2256 | 1.78 | 48905 |
| | | 5 | 1.2725 | .32409 | .2546 | .6 | 52702 |
| | | 6 | 1.2126 | .32669 | .2694 | .878 | 45363 |

Table VI: Comparison of optimum arches under dynamic load

| L(m) | | | $t_0(m)$ | $t_1(m)$ | $K$ | $\overline{W}/H$ | $(\sigma_t)_{ma}$ |
|---|---|---|---|---|---|---|---|
| Tudor arch | diminished | 4 | 1 | .3 | .3 | *.38* | *47049* |
| | | 5 | .96541 | .22347 | .2314 | .52 | 53843 |
| | | 6 | .81758 | .20173 | .2467 | 2.46 | 45479 |
| | normal | 4 | .94988 | .21925 | .2308 | .602 | 46598 |
| | | 5 | 1.0553 | .26254 | .2487 | 2.93 | 49234 |
| | | 6 | 1.1021 | .33083 | .3001 | 7.71 | 49909 |
| | steep | 4 | 1 | .3 | .3 | 1.018 | 45254 |
| | | 5 | 1.0055 | .21145 | .2102 | .428 | 46968 |
| | | 6 | 1.0081 | .20728 | .2056 | .746 | 53990 |

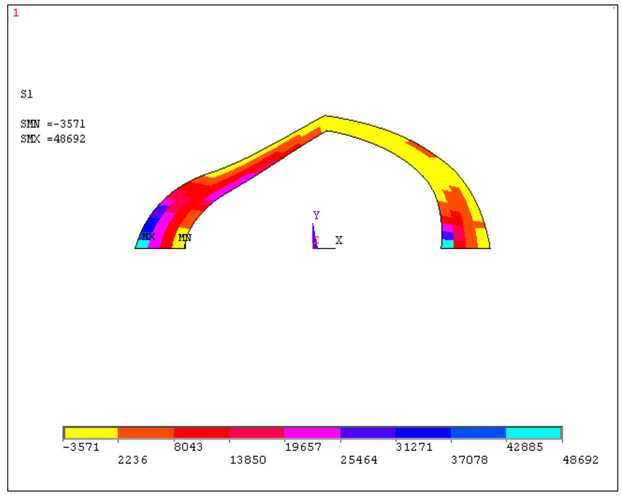



Fig IV: Lancet arch modeling by ansys

Table VII: Comparison of optimum arches under dynamic load

| L(m) | | $t_0(m)$ | $t_1(m)$ | $K$ | $\overline{W}/H$ | $(\sigma_t)_{max}$ |
|---|---|---|---|---|---|---|
| Equilateral arch | 4 | .82923 | .2073 | .2499 | .4876 | 46137 |
| | 5 | 1.0769 | .2776 | .2577 | 1.955 | 53033 |
| | 6 | 1.2125 | .32458 | .2676 | .708 | 52903 |
| Fourcentered arch | 4 | 1.0875 | .32358 | .2975 | *2.2* | 52845 |
| | 5 | 1.0945 | .34641 | .3165 | .39 | 51515 |
| | 6 | 1.1457 | .35342 | .3079 | .63 | 50091 |

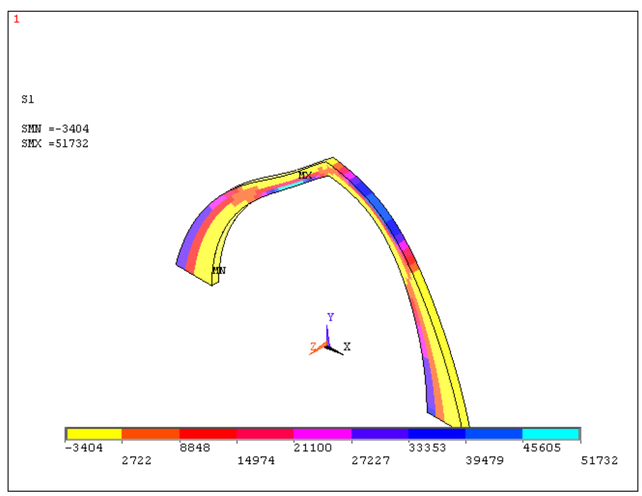



Fig V: Obtuse angel arch modeling by ansys

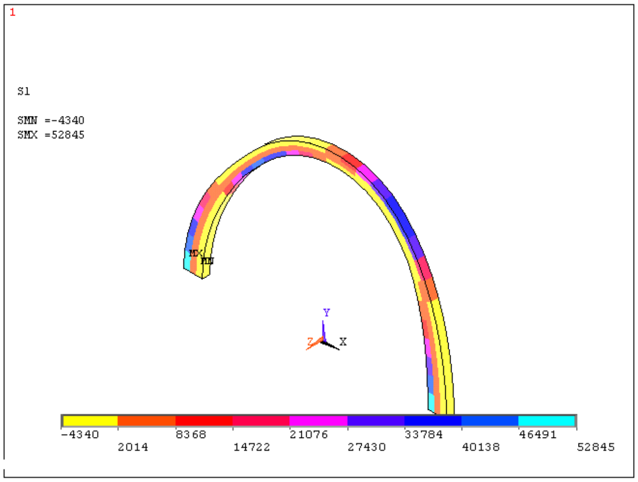



Fig VI: Tudor arch modeling by ansys

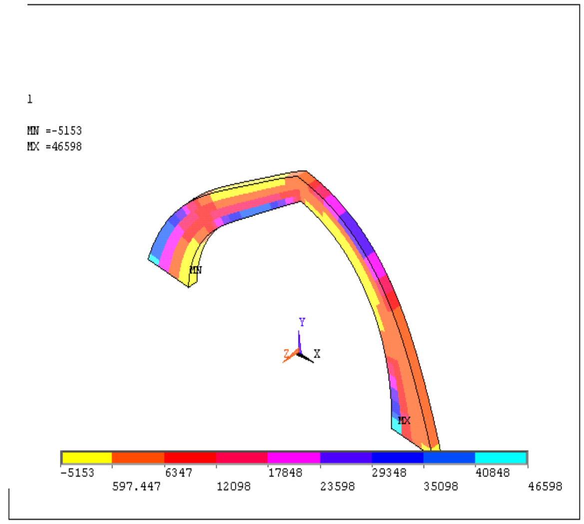



Fig VII: Catenary arch modeling by ansys

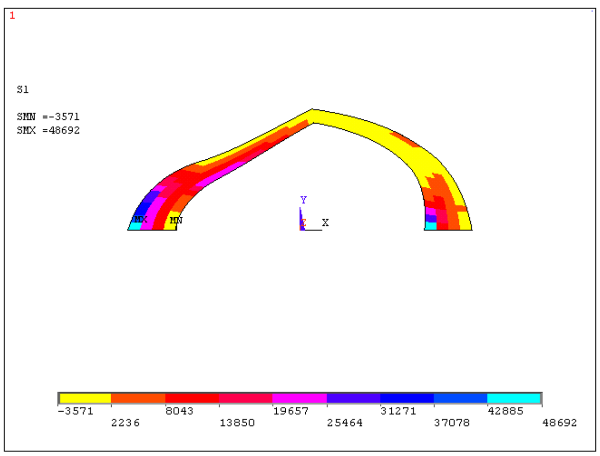



Fig VIII: equilateral arch modeling by ansys

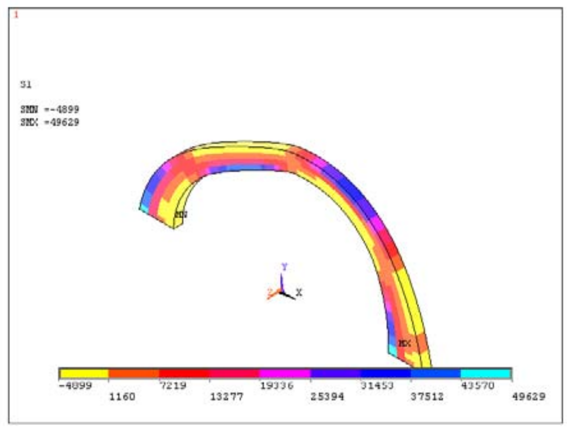



Fig IX: Fourcentered arch modeling by ansys

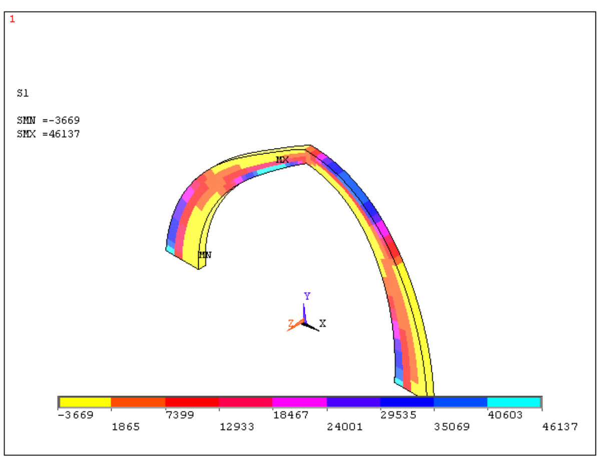



Fig X: Four centered pointed arch modeling by ansys

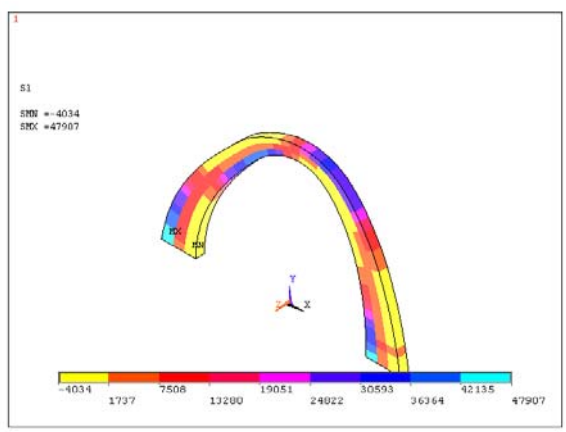



Fig XI: Ogee arch modeling by ansys

Table VIII: Comparison of optimum arches (dynamic load)

| L(m) | | | $t_0(m)$ | $t_1(m)$ | $K$ | $\overline{W}/H$ | $(\sigma_t)_{max}$ |
|---|---|---|---|---|---|---|---|
| Obtuse angel arch | diminished | 4 | 1 | .3 | .3 | .428 | 51732 |
| | | 5 | 1.0692 | .32387 | .3029 | 6.32 | 47999 |
| | | 6 | 1.1662 | .32977 | .2827 | .807 | 45882 |
| | normal | 4 | 1.0975 | .25091 | .2286 | 1.49 | 51981 |
| | | 5 | 1.1472 | .30751 | .268 | 5.72 | 53113 |
| | | 6 | 1.1606 | .31979 | .275 | .193 | 51373 |
| | steep | 4 | .96942 | .1798 | .1854 | .55 | 45853 |
| | | 5 | 1.0975 | .25091 | .2286 | .135 | 53922 |
| | | 6 | 1.1769 | .30722 | .261 | 7.3 | 52566 |
| Four centered pointed arch | diminished | 4 | .83728 | .24854 | .2968 | .887 | 46341 |
| | | 5 | 1.1309 | .32538 | .2877 | 1.156 | 50859 |
| | | 6 | 1.1472 | .33751 | .2942 | 3.94 | 47815 |
| | normal | 4 | 1.0682 | .27979 | .2619 | 4.62 | 48692 |
| | | 5 | .98693 | .34854 | .353 | 5.69 | 45980 |
| | | 6 | .98287 | .36943 | .3758 | .471 | 53175 |
| | steep | 4 | .89212 | .34194 | .3832 | .32 | 47463 |
| | | 5 | .9222 | .3546 | .386 | .589 | 47367 |
| | | 6 | .98992 | .37287 | .376 | 5.01 | 49506 |

Table IX: Comparison of optimum arches(static load)

| L(m) | | | $t_0(m)$ | $t_1(m)$ | $K$ | $t_0/R$ | $t_1/R$ | $\overline{W}/H$ | $(\sigma_t)_{ma}$ |
|---|---|---|---|---|---|---|---|---|---|
| Obtuse angel arch | diminished | 4 | .7 | .27 | .38 | .35 | .13 | 4.15 | 51526 |
| | | 5 | .748 | .29 | .38 | .3 | .11 | 4.15 | 48326 |
| | | 6 | .816 | .2967 | .36 | .27 | .1 | 4.15 | 50545 |
| | normal | 4 | .768 | .2258 | .29 | .38 | .11 | 4.5 | 50256 |
| | | 5 | .803 | .2767 | .34 | .32 | .1 | 4.5 | 49400 |
| | | 6 | .8124 | 2878. | .35 | .27 | .1 | 4/5 | 49568 |
| | steep | 4 | .6785 | .1618 | .238 | .34 | .1 | 5 | 51489 |
| | | 5 | .7682 | .225 | .29 | ..3 | .1 | 5 | 51026 |
| | | 6 | .8238 | .2764 | .335 | .27 | .1 | 5 | 51092 |

Table X: Comparison of optimum arches
(static load)

| L(m) | | | $t_0(m)$ | $t_1(m)$ | $K$ | $t_0/R$ | $t_1/R$ | $\overline{W}/H$ | $(\sigma_t)_{max}$ |
|---|---|---|---|---|---|---|---|---|---|
| four centred pointed arch(static analysis) | diminished | 4 | .58 | .22 | .38 | .29 | .11 | 1.6 | 48525 |
| | | 5 | .79 | .29 | .37 | .32 | .11 | 1.6 | 50145 |
| | | 6 | .8 | .30 | .38 | .26 | .1 | 1.6 | 51526 |
| | normal | 4 | .75 | .25 | .33 | .37 | .12 | 1.95 | 49411 |
| | | 5 | .7 | .31 | .45 | .27 | .12 | 1.95 | 49980 |
| | | 6 | .68 | .33 | .49 | .22 | .11 | 1.95 | 52111 |
| | steep | 4 | .62 | .30 | .49 | .31 | .15 | 2.4 | 49881 |
| | | 5 | .64 | .31 | .49 | .25 | .12 | 2.4 | 50101 |
| | | 6 | .69 | .33 | .47 | .23 | .11 | 2.4 | 51211 |

Table XI: Comparison of optimum arches
(static load)

| L( m) | | $t_0(m)$ | $t_1(m)$ | $K$ | $t_0/R$ | $t_1/R$ | $\overline{W}/H$ | $(\sigma_t)_{max}$ |
|---|---|---|---|---|---|---|---|---|
| equilateral arch | 4 | .67 | .16 | .24 | .34 | .1 | 4.9 | 51105 |
| | 5 | .74 | .18 | .25 | .3 | .1 | 4.9 | 49411 |
| | 6 | .79 | .25 | .32 | .26 | .1 | 4.9 | 49881 |

## V. DETERMINATION OF LIMITS IN LINEAR AND NON LINEAR ANALYSIS BY INCREASE OF DENSITY

### B.A. Evaluation And Comparison Of Linear And Nonlinear Limits In Semi Circular And Obtuse Angel Arches By Density Factor

In this part, linear and nonlinear analysis of semicircular arches with span of 5m and obtuse angle arch with span of 4 m has been studied. Also, the density is applied to evaluation of linear and nonlinear analysis. This was also noticed that in which limits the maximum tension stress (the arch optimization factor) can change (table XII). [6,13,15]

Table XII: Comparison between linear and nonlinear limits by density factor(dynamic load)

| | $\rho = 1460\ kg/m^3$ | | $\rho$ | 1.5 $\rho$ | 2 $\rho$ | 3 $\rho$ | 4 $\rho$ |
|---|---|---|---|---|---|---|---|
| Semicircular arch | Linear Analysis | $(\sigma_t)_{\max}$ | 212921 | 148307 | 94944 | 60169 | 48072 |
| Semicircular arch | Non Linear Analysis | $(\sigma_t)_{\max}$ | 225149 | 148307 | 94944 | 60169 | 48072 |
| Obtus angel arch | Linear Analysis | $(\sigma_t)_{\max}$ | 856833 | 267317 | 248307 | 211944 | 183337 |
| Obtus angel arch | Non Linear Analysis | $(\sigma_t)_{\max}$ | 593918 | 267317 | 248307 | 211944 | 183337 |

According to results of test and error (table 2), if density is higher than 4 $\rho$, the response of linear and nonlinear stress is different. So for linear analysis, increase of density to 4 $\rho$ is ineffective. [6,9,10]

### *B.B. Evaluation* And Comparison Of Optimum Shape In Semicircular And Obtus Angle Arch By Linear And Non Linear Analysis

The optimum shape of semicircular arch and obtus arch with spans of 4m have been calculated by linear and nonlinear analysis and density of 4 $\rho$ .Then the results compared to the optimum shape of semicircular and obtus by linear analysis and density of $\rho$ (TableXIII). [8,12,16]

Table XIII: Comparison of optimum shape in semicircular and Obtus angle arches with of 4m spans by linear and nonlinear analysis (dynamic load)

| density | | Kind of analysis | $t_0$ | $t_1$ | $k$ |
|---|---|---|---|---|---|
| Semicircular arch | $\rho$ | Linear Analysis | .8328 | .2763 | .3317 |
| Semicircular arch | $\rho$ | Non Linear Analysis | .8328 | .2763 | .3317 |
| Semicircular arch | 4 $\rho$ | Linear Analysis | 1.3 | .2921 | .2247 |
| Semicircular arch | 4 $\rho$ | Non Linear Analysis | 1.541 | .3344 | .2168 |
| Obtuse angel arch | $\rho$ | Linear Analysis | .9694 | .1798 | .1854 |
| Obtuse angel arch | $\rho$ | Non Linear Analysis | .9694 | .1798 | .1854 |
| Obtuse angel arch | 4 $\rho$ | Linear Analysis | 1.332 | .3 | .2269 |
| Obtuse angel arch | 4 $\rho$ | Non Linear Analysis | 1.609 | .3886 | .241 |

Continue of Table XIV: Comparison of optimum shape in semicircular and Obtus angle arches with of 4m spans by linear and nonlinear analysis. (dynamic load)

| density | | Kind of analysis | $W$ | $H$ | $\overline{W}/H$ | $(\sigma_t)_{\max}$ |
|---|---|---|---|---|---|---|
| Semicircular arch | $\rho$ | Linear Analysis | 917.2 | 1057.8 | .4347 | 50982 |
| | $\rho$ | Non Linear Analysis | 917.2 | 1057.8 | .4347 | 50982 |
| | 4 $\rho$ | Linear Analysis | 5641.1 | 4052 | .69 | 51700 |
| | 4 $\rho$ | Non Linear Analysis | 6681 | 4471 | .747 | 53873 |
| Obtuse angel arch | $\rho$ | Linear Analysis | 1188 | 1079.3 | .552 | 45853 |
| | $\rho$ | Non Linear Analysis | 1188 | 1079.3 | .552 | 45853 |
| | 4 $\rho$ | Linear Analysis | 5781 | 5012 | .576 | 52853 |
| | 4 $\rho$ | Non Linear Analysis | 6483 | 5221 | .62 | 53541 |

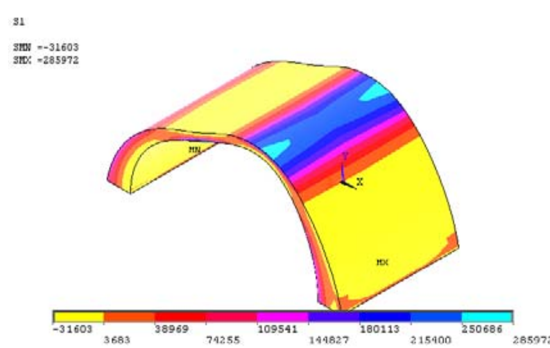
## VI. THE SYUDY AND COMPARISION LINEAR AND NONLINEAR ANALYSIS OF SEMICIRCULAR VAULTS WITH SPAN OF 5M BY DENSITY

The results are as below:

Table XV: the results of study of linear and nonlinear analysis by density. (dynamic load)

| $\rho = 1460\ kg/m^3$ | | $\rho$ | 1.5 $\rho$ | 1.6 $\rho$ | 1.7 $\rho$ | 2 $\rho$ |
|---|---|---|---|---|---|---|
| Linear analysis | $(\sigma_t)_{\max}$ $(N/m^2)$ | 207607 | 488911 | 538909 | 1180000 | 6550468 |
| Nonlinear analysis | | 207607 | 488911 | 532170 | 918847 | 388641 |

As the results show(table 10-3), for densitis which are higher than 1/6 , the linear and nonlinear stresses are diffrent to each other. Also, in analysis of semicircular arches , the place of maximum tensile stress is around of inner shield, near base of arch and in the middle of arch lenghth.Also,maximum compressive stress is around of outter shield near base of arch(figXII).[11,12,14]



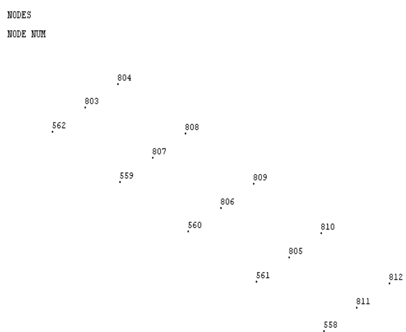

FigXII:semicircular arch with 4m spam and the place of stresses( $N/m^2$ )

## VII. ESTIMATION OF BASE THRUST FORCE IN X DIRECTION

According to this point that $\overline{W}/H$ (the weight of half of arch to thrust force in one side) is a main criteria in arch resistence, the way of thrust force estimation is very important. Because of in modelling, we suppose that all of supports are restrained, so all of joints in $Y = 0$ has a horizontal force that its source is earthquake force that is stimated by Reaction Solution processor and estimated in *ANSYS* software. For example, for estimation of thrust force for half of arch span (radius=2m), is shown in( fig.XII ). [5,8,15]

```
PRINT FX   REACTION SOLUTIONS PER NODE

 ***** POST1 TOTAL REACTION SOLUTION LISTING *****

 LOAD STEP=  1500  SUBSTEP=     1
  TIME=    30.000      LOAD CASE=   0

 THE FOLLOWING X,Y,Z SOLUTIONS ARE IN GLOBAL COORDINATES

   NODE       FX
    558  -107.83
    559  -46.297
    560  -49.527
    561  -122.34
    562  -59.980
    803  -112.60
    804  -59.980
    808  -46.297
    809  -49.527
    810  -122.34
    811  -173.27
    812  -107.83

TOTAL VALUES
VALUE   -1057.8
```

FigXIII-a:estimation of thrust force at x direction




FigXIII-b:estimation of thrust force at x direction

## VIII.CONCLUSION

Considering to optimum shape in arches under dynamic load, several conclusions can be surmised from the results as follow:

1-With increase of masonry density, the difference between maximum tensile stress in linear and nonlinear analysis reveals. It means that the increase of density to 4 $\rho$ for linear and non linear analysis is ineffective.

2- The limit for increase of base thickness in linear and nonlinear analysis for 4 $\rho$ : $\rho$ is 36 to 93%.

3- The limit for increase of top thickness in linear and nonlinear analysis for 4 $\rho$ : $\rho$ is 66 to 116%.

4-Increase of $\varpi$ / H in linear and nonlinear analysis for 4 $\rho$ : $\rho$ is 12%.

5- Increase of arch base thickness in nonlinear analysis of 4 $\rho$ to linear analysis of 4 $\rho$ is 21%.

6- Increase of arch top thickness in linear analysis of 4 $\rho$ to linear analysis of 4 $\rho$ is 30%.

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