Direct Displacement Control of Deformed Double Layer Dome

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ABSTRACT

Space structures such as a double layer dome are light and active structural systems that are used for various structural applications, for instance, structural covers over large areas such as exhibition halls, stadiums, and concert halls. They are aesthetically pleasing in appearance, and serve the architectural requirement as well. The tolerances of structural shape under changing service conditions are important, and high appearance accuracy is required in some applications. Because of many reasons such as loadings, these type of structures may suffer from a noticeable deflection, which leads to a significant potential undesired appearance of the shape. In this situation, the displacements may need to be reduced or eliminated. In this study, by applying the shape adjustment technique, which depends on the linear force method, shape restoration is performed to the double layer dome model in three different cases corresponding to the directions of loadings as vertical, horizontal, and simultaneously vertical and horizontal were considered. The improvement of controlling nodal displacement can be achieved by using a rather simple and direct method, calculating necessary length of actuators by applying a single formulation. It is found that if the number of provided actuators are satisfactory, controlling of all the displaced joints could be performed and all the target joints could be restored to their original positions by a very small percentage of discrepancy as 0.5%, 1.8%, and 0.02% for the three considered cases, even if the controlled joints connection is not direct with the adjustable members. The technique of shape adjustment is very efficient for double layer dome model, and it can roughly eliminate the displacement of definite joints (exterior joints only) by simply changing the length of certain bars by a small amount. The values of the total actuations are 874.95 mm, 246.25 mm, and 1150.8 mm in Cases 1, 2, and 3, respectively. Moreover, some of the members approve the better role in controlling the displaced joints as they are duplicated in all load cases, and they are sited in the inner layer of the double layer dome model.

Keywords: Force method, Actuation, Shape restoration, Displacement control, Double layer dome.

1. INTRODUCTION

In the past decades, there has been a growing number of structures using steel domes to cover large areas (Chen and Lui, 2005). Domes are one of the oldest magnificent structural systems. They consist of one or more layers of elements that are arched in all directions (Jayminkumar and Vahora, 2016). Domes are used to cover large areas such as exhibition halls, stadiums, and concert halls (Jayminkumar and Vahora, 2016) because they are lightweight and cultured assemblies that provide cost-effective solutions for covering large areas with their splendid aesthetic exterior. Devoid of disturbing columns in the interior with efficient shapes, dome covers the all-out volume and economy in terms of materials (Chen and Lui, 2005; Jayminkumar and Vahora, 2016). The geometry of the structure is an important aspect to prearrange the behavior, capacity utilization, and...
the heaviness of the structures (Chen and Lui, 2005).

Structural geometry is usually well-defined by determining nodal positions in both esthetical and functional aspects. The esthetical aspect includes egg-shaped space structures (Saeed et al., 2019), cable stayed bridge (Saeed and Kwan, 2017), and cable arch stayed bridges (Manguri et al., 2017; Saeed, 2019), whereas examples for functional aspect are antenna reflectors (You, 1997), large space antenna (Weeks, 1984), tetrahedral truss antenna reflector (Haftka and Adelman, 1985), space structures (Saeed et al., 2019), and cable stayed bridge (Saeed and Kwan, 2017). A high precision in those structural geometries with a high grade of accuracy is desired (Saeed et al., 2019; Saeed and Kwan, 2017; You, 1997).

However, the shape distortion of the structure is inevitable because of fatigue, imperfection in manufacturing, temperature deformation, unpredicted loading, and looseness in joints. As soon as the disfiguration shape is considered intolerable, the nodal positions require to be restored to its original shape. The technique of shape control/adjustment can be defined as reduction or even elimination of the structural deformation caused by external disturbances (Ziegler, 2005). Because of the capability of some members to elongate or shorten their length, the computational technique of shape restoration can be achieved (Manguri et al., 2017; Saeed et al., 2019; Saeed and Kwan, 2017; Saeed and Kwan, 2016; Shea et al., 2002; Xu and Luo, 2009; You, 1997). In addition, You (1997), as a straight issue, carried out the relation between the length of actuators and nodal displacements for not loaded prestressed structures. Saeed and Kwan (2016) provided a method to directly dominate nodal displacements by altering active members for structures distorted under loading.

Shape control/adjustment has been carried out on the different types of structures in order to eliminate the distortion of the shape geometry, for instance, the shape control of beam (Hadjigeorgiou et al., 2006; Yang and Ngoi, 2000; Yu et al., 2009), cable mesh antennas (Du et al., 2014; Mitsugi et al., 1990; Tanaka, 2011; Tanaka and Natori, 2006; Tanaka and Natori, 2004; Wang et al., 2013), intelligent structures (Wang et al., 1997), truss structures (Saeed and Kwan, 2016; Trak and Melosh, 1992), tensegrity structures (Shea et al., 2002), structural assemblies including complex elements “macro-elements,” e.g., the pantographic element (Saeed and Kwan, 2016b), cable arch stayed bridges (Manguri et al., 2017; Saeed, 2019), and egg-shaped single layer space frames (Saeed et al., 2019).

In this study, the dome structure that is formed of two layers with interconnected elongated members is presented as a theoretical model that could undergo a great deformation under gravity loads or/and lateral loads. However, previously, the shape adjustment technique for space structure as the three dimensional egg-shaped single layer has been carried out by Saeed et al. (2019). Nonetheless, the displacement control was made only for vertical deformation that has been done by vertical loading only through adding the actuators as extra members before the stage of loading. It could be done during/after the process of construction to perform the process of adjustment, which means that the own members of the egg-shaped single layer space frame didn’t participate in the adjustment process. Consequently, the focus of this paper is on the shape restoration by controlling deformation in all directions due to gravity loads or/and lateral loads by using the own members of the dome model as actuators.

The purpose of this paper is to use a direct relationship between bar length actuations and the nodal position/displacements for adjusting shape imperfection of the theoretical model of the double layer dome. This has been done using the method already derived by Saeed and Kwan (2014; 2016), using MATLAB program and validating by SAP2000 software. Besides, finding where the actuator should be placed led to the minimal amount of actuation, and it is possible to choose the optimal number of actuators.

2. GEOMETRY OF THE STRUCTURE AND LOADING
The structural assembly of the double layer dome and the properties of materials and loadings are represented as follows.

### 2.1. Geometry

The generation of the dome geometry is coded in MATLAB program as given in Fig. 1. The structure is analyzed through the force method. The theoretical model of double layer dome consists of 201 nodes and 760 members, which are arranged on the form of ribbed pattern to develop the dome model. The dome model has a diameter of 4000 mm with the ratio of span to height of 2. Moreover, the distance between both layers is indicated to be 100 mm, the ratio of its thickness to the diameter is 1/40, which is in the range of 1/30 to 1/60, as described by Chen and Lui (2005). The geometry is supported by 20 pinned supports along the perimeter, as shown in Fig. 2.

### 2.2. Properties of Materials

All members have been selected to have circular cross section with $EA = 5.6549 \times 10^6$.

### 2.3. Loading

The structure has been loaded according to the three cases of loadings. In Case 1, the structure is loaded by 20 kN of gravity point loads on the exterior nodal positions as shown in Fig. 3. In Case 2, the structure is loaded by 5 kN point loads laterally on the exterior nodal positions as shown in Fig. 4. Finally, in Case 3, the structural geometry of the double layer dome model is loaded simultaneously by vertical and horizontal point loads of 20 kN and 5 kN, respectively, as shown in Fig. 5. Afterward, the geometry of the double layer dome model underwent a noticeable distortion in appearance, which is unacceptable. Hence, the technique of the shape restoration becomes necessary, as is stated in the following sections.

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**Figure 1.** MATLAB program code for geometry generation of the double layer dome model

```matlab
% Double Layer Ribbed Dome Geometry
Nr=20; Nc=6; %Nr: is no. of meridians & Nc: is no. of circles
R=2000; Thic=100; % external radius (mm) & distance between two layers (mm)
Layer=2; j=0; w=0; Theta=0; %Layer: no. of layers, Theta: horizontal & vertical angle in degree
for Ly=1:Layer; for k=1:Nc-w; for i=1:Nr; j=1;
    coor(j,1)= R*cos(Alpha)*cos(Theta); coor(j,2)= R*cos(Alpha)*sin(Theta); coor(j,3)= R*sin(Alpha); Th=Th+360/Nr;
    end; Alpha=Alpha+90/(Nr-1); end; Th=360/(2*Nr); Alpha=90/(2*(Nr-1)); w=w+1; R=R-Thick; end;
    coor(coor([1:100,121:220,101],:));
    for i=1:120; bar(i,1)=i; bar(i,2)=i+1; end; for i=1:20:101; bar(i,19,2)=i; end; %outer circle
    for i=121:200; bar(i,1)=i; bar(i,2)=i+1; end; for i=121:20:101; bar(i,19,2)=i; end; %inner circle
j=1; %outer connection between circles
j=1; for i=201:280; bar(i,1)=j; bar(i,2)=j+20; j=j+1; end; for i=281:300; bar(i,1)=j; bar(i,2)=201; j=j+1; end
for i=301:350; bar(i,1)=j; bar(i,2)=20; j=j+1; end; for i=381:400; bar(i,1)=j; bar(i,2)=201; j=j+1; end
i=101; k=1; i=i+1; % Connection between Two Layers
for h=1:4; for f=1:20; bar(i,1)=j; bar(i,2)=k; i=i+1;
    bar(i,1)=j; bar(i,2)=k+1; i=i+1; bar(i,1)=j; bar(i,2)=k+20; i=i+1;
    bar(i,1)=j; bar(i,2)=k+21; i=i+1; bar(i,1)=j; bar(i,2)=k+41; i=i+1;
end; for f=1:20; bar(i,1)=j; bar(i,2)=k; i=i+1; bar(i,1)=j; bar(i,2)=k+1; i=i+1; j=j+1; k=k+1; end
bar(400,2)=1; bar(550,2)=21; bar(640,2)=41; bar(720,2)=61; bar(760,2)=91;
plot3([0 3], [0 3], 'w'); hold on
for i=1:760; j=bar(i,1); j2=bar(i,2);
    plot3(coor(j,1), coor(j,2), [coor(j,2), coor(j2,2), [coor(j,2), coor(j,1), 'o-', 'LineWidth',1, 'Color','blue']); end;
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Figure 2. Geometry of double layer ribbed dome model

Figure 3. Double layer dome model (a) under vertical loading (b) deformed shape
Abdulkarim et al.: Direct Displacement Control of Deformed Double Layer Dome

Figure 4. Double layer dome model (a) under horizontal loading (b) deformed shape

Figure 5. Double layer dome model (a) under vertical and horizontal loading simultaneously (b) deformed shape.
3. METHODOLOGY AND TECHNIQUE

The utilized technique of shape adjustment, based on the force method (Kwan, 1991; Pellegrino, 1993; Pellegrino et al., 1992), to allow “easy access” to the contributing parameters for the external displacements and internal deformation has been derived by Saeed and Kwan (2014; 2016). The current technique has been used for controlling of external deformation, internal force, and external deformation with internal force simultaneously, but in this paper, only the shape control is focused on. Eqn. 1 is the main equation of the technique, which is:

\[ d = Ye_o + dp \]  

(1)

where \( Y = B^+ - B^+ FS(S^TFS)^{-1} S^T \), and \( dp = [B^+ F - B^+ FS(S^TFS)^{-1} S^T F]t_A \) is the vector of nodal displacements of the structure due only to load, and \( d \) is the resultant nodal displacements after some elongation actuation \( e_o \) has been applied. The vector \( d \), in whole or in part, can thus be used as the prescribed displacements, and eqn. 1 then provides the required corrective \( e_o \) to achieve that prescribed \( d \), despite the effects of load in \( dp \).

Clearly, \( Y \) is generally not a square matrix and need not even be of full rank. Furthermore, it is likely that only a few elements of \( d \) need to be controlled, and not all elements of \( e_o \) would typically be actuated. The system of equations and unknowns in eqn. 1 is thus normally likely to be only a small subset of the full set of equations. In view of all this, the solution for \( e_o \) is thus best obtained using the pseudoinverse of \( Y \). For more straightforwardness and achieving elongation actuation \( e_o \) directly, eqn. 1 becomes:

\[ e_o = Y^+[d - dp] \]  

(2)

4. RESULTS

In terms of applying different direction of loadings as vertical loadings, horizontal loadings, and both vertical and horizontal loadings simultaneously, three different situations are taken under consideration, namely, Case 1, Case 2, and Case 3, respectively. The target displacement of the model is restoring the surface shape to its original configuration (i.e., making all exterior joints have zero deflection in all directions \( X, Y, \) and \( Z \)) as shown in Column 5 in Tables 1-3. The number of total exterior joints is 81, which is determined from eqn. 2. The results of the displacement control for all the cases are presented in Tables 1-3, and the restored shapes of Cases 1, 2, and 3 are shown in Figs. 6, 7, and 8, respectively.

4.1. Shape Restoration under Vertical Loading Only (Case 1)

The double layer dome model is loaded by 20 kN of vertical point loads on the exterior joints, which are 81 joints, and the model confronted a great deformation as shown in Fig. 3. The X, Y, and Z directions of nodal displacement of joints (\( dp \)) after applying the loads are presented in Columns 2-4 of Table 1. Moreover, it can be noticed that the displacements in the direction of \( Z \), which are matching with the direction of loadings are greater than displacements of both of \( X \) and \( Y \) directions.

Shape Restoration for Case 1: The desired target (\( dt \)) for restoring the displaced joints of exterior nodes (Column 1) for the double layer dome model are specified to be zero for all the directions as fixed in Column 5 of Table 1 by using the equation of adjustment (eqn. 2) (Saeed and Kwan, 2014, 2016). The shape adjustment technique has been performed and applied to the theoretical model via MATLAB program. A set of \( e_o \) is calculated to attain the desired target configuration, which is shown in Column 12 of Table 1. After applying this set of actuation \( e_o \) for the selected members (Column 14) of the deformed shape of the double layer dome model, the results of nodal displacements from the MATLAB program are presented in Columns 6-8 in Table 1. For the purpose of checking, another software SAP2000 is also used, and the offered results are showed in Columns 9-11. The results are very correlative with the achieved displacement results from the MATLAB program. All displacement of the post-adjustment in Columns 6-11 are very close to the desired target displacements in Column 5. The tiny
discrepancy between the desire targets and the theoretical outcomes in this case were observed as shown in Fig. 6, which it is only 0.5% as a maximum discrepancy. The total amount of actuation by using 160 members of inner layer of the double layer dome model is 847.95 mm.

At the beginning stages of shape adjustment in the MATLAB program, all members of inner layer and all the interconnected members between inner and outer layers are chosen to participate in the shape restoration technique as actuators, which add up to 520 members. However, these stages provide the exact shape restoration as the desired target ($d_T$), but using the 520 members is not economical and not applicable for the practical request. Therefore, depending on the $Y$ in eqn. 2, that is totally governed by the geometry of the structure. The most active members, which have the larger coefficient values of $Y$, are chosen to perform the shape adjustment with fewer number of actuators. Finally, by after inspection as carried out by Saeed and Kwan (2016) through reselection of bars, the number of actuators are reduced to only 160 members. The results are very close to the desired target with the maximum discrepancy not exceeding 0.35 mm, as shown in Fig. 6.

For Case 1, where the direction of loadings is vertical, the active members that perform all the role in the shape adjustment technique are those members that are positioned in the inner layer of the double layer dome model. Besides, the interconnected members do not confirm a significant function for the shape restoration technique. In addition, the number of actuators still can be reduced, but as a consequence, it increases the range of maximum discrepancy.

Figure 6. Double layer dome model under vertical loading (a) Pre-adjustment (b) Post-adjustment
Table 1: Shape restoration of the Dome Model under vertical loading only

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Total actuation (mm) 847.95

*These numbers have the opposite sign in x-direction.
4.2. Shape Restoration under Horizontal Loading Only (Case 2)

In this case, the double layer dome model is laterally loaded in Y direction by 5 kN of point loads on the half part of the exterior joints, which are 36 joints, and the model displayed a noticeable deformation, as shown in Fig. 4. The displacements of X, Y, and Z directions of joints \( \mathbf{d}_P \) after affecting by the loads are presented in Table 2 in Columns 2-4. Likewise, it can be noticed that the displacements in the Y direction, which are parallel to the load direction, have the greatest value compared with the other directions for all the joints.

Shape Restoration for Case 2: Same as the Case 1, the desired target \( \mathbf{d}_T \) that should be restored for the displaced joints of exterior nodes (Column 1) for the double layer dome model is specified to be zero for all the directions X, Y, and Z, as shown in Column 5 of Table 2. From eqn. 2, a group variety of \( \mathbf{e}_o \) is determined to achieve the desired target shape, which is demonstrated in Columns 12 and 13 of Table 2. After stratifying this set of length alteration \( \mathbf{e}_o \) for the nominated members in Column 14, the theoretical result \( \mathbf{d} \) (Columns 6-11) is very close to the desired target (Column 5). The results of this case are also validated by the SAP2000 software, which are very correlative with the achieved displacement results from the MATLAB program as shown in Columns 9-11. The amount of 246.25 mm is the total actuation for 80 members of inner layer and interconnected members of the double layer dome model. Correspondingly, the difference between the desired targets and the theoretical outcomes in this case, as the maximum discrepancy is 1.8% roughly.

Similar to the Case 1, all of the 520 members (inner layer and interconnected members) are specified to effort as the actuators and gave the amount of \( \mathbf{d} \) as the exact value of desired target of the controlled displacement. In the next stages, depending on the reselection of bars (Saeed and Kwan, 2016), the number of actuators are decreased to 80. These number of members as the actuators provide an acceptable outcome to the desired target within the maximum discrepancy equal to 0.56 mm (1.8%), as shown in Fig. 7. In this Case, where the direction of loadings is only within the horizontal Y direction, the active members that perform the shape adjustment technique are located in the inner layer and the interconnected members of the double layer dome model. Moreover, the interconnected members play an important role in the shape restoration technique. If the actuators are compared between both Cases 1 and 2 in Column 14 of Tables 1 and 2, there are 26 members that are duplicated in the adjustment process that are located in the inner layer of the double layer dome model. Furthermore, the number of actuators can be further reduced, but it will increase the range of maximum discrepancy.

![Figure 7. Double layer dome model under horizontal loading (a) Pre-adjustment (b) Post-adjustment](image)
4.3. Shape Restoration under Vertical and Horizontal Loading Simultaneously (Case 3)

In this case, the double layer dome model is laterally loaded in Y direction by 5 kN and also vertically loaded in Z direction by 20 kN simultaneously. The model is exposed to an observable distortion, as shown in Fig. 5. The considerable situation is that some of the displacements of X, Y, and Z directions of the joints due to the loadings are considered to be unacceptable. Therefore, the geometry of the model should be restored by using some actuators that should be imbedded to the most active bars, as presented in Columns 2-4 of Table 3. Compatibly, the double layer dome model in Case 3 behaves like the model in Case 1 corresponding to the Z direction, whereas it behaves like the model in Case 2 for X and Y directions. Nonetheless, all the values of the displacements are less than the corresponding displacement of the two former cases.

Table 2: Shape restoration of the Dome Model under horizontal loading only

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<th>d_t (mm)</th>
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<td>0.12</td>
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<td>-4.50</td>
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<td>54,58'</td>
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<td>-0.23</td>
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<tr>
<td>55,57'</td>
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<td>0.07</td>
<td>54.54</td>
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<tr>
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<td>0.00</td>
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<tr>
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<tr>
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<tr>
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<td>70.70</td>
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<td>76</td>
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<td>-0.35</td>
<td>0.07</td>
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</tr>
<tr>
<td>81,91'</td>
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<td>0.11</td>
<td>-0.26</td>
<td>0.21</td>
<td>74.74</td>
</tr>
</tbody>
</table>
Shape Restoration for Case 3: As mentioned in the two earlier cases, the desired target \( \mathbf{d}_T \) for exterior joints (Column 1) of the double layer dome model is indicated to be zero for the three dimensional directions as presented in Column 5 of Table 3. The determined set of \( \mathbf{e}_n \) due to applying eqn. 2 has been calculated and managed in Columns 12 and 13 in Table 3 after applying this set of member actuation \( (\mathbf{e}_n) \) for the selected members of the theoretical model (Column 14). The outcomes of restored displacement \( \mathbf{d} \) by SAP2000 software, which are very correlative with the achieved displacement by MATLAB program, are presented in Columns 6-11; correspondingly, the results are very close to the desired target (Column 5), with the maximum discrepancy of 0.18 mm (0.02%). The total amount of actuation by requesting 203 members of inner layer and interconnected members of the double layer dome model is only 1150.8 mm.

Similarly, for all the cases at the establishment stages, all the members except the exterior members, which are 520 members, are chosen to contribute in the process of restoration as actuators. However, the outcome \( \mathbf{d} \) of utilizing all these members provides the exact shape restoration as the desired target \( \mathbf{d}_T \), as in both previous cases. However, using the 520 members will be costly and not applicable for hands-on application. Therefore, depending on the maximum coefficient of \( Y \) in eqn. 2 (Saeed and Kwan, 2016), the most active members are chosen to perform the shape adjustment technique, as shown in Fig. 8.

For Case 3, where the direction of loadings is vertical and horizontal simultaneously, the active members that accomplish the performance in the shape adjustment technique are both of the interconnected members and inner layer members of the dome model. In addition, the duplicated members between Cases 1 and 2 are kept to participate in the shape restoration technique. Furthermore, the number of elongation members can be reduced, but this reduction will increase the range of maximum discrepancy and shows greater variance between the desire target and obtained nodal displacement.

<table>
<thead>
<tr>
<th>Table 3: Shape restoration of the Dome Model under vertical and horizontal loading simultaneously</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<tr>
<td>Joints</td>
</tr>
<tr>
<td>X</td>
</tr>
<tr>
<td>1-20</td>
</tr>
<tr>
<td>21.3′</td>
</tr>
<tr>
<td>22.3′</td>
</tr>
<tr>
<td>23.2′</td>
</tr>
<tr>
<td>24.2′</td>
</tr>
</tbody>
</table>

Total actuation (mm) 246.25
These numbers have the opposite sign in x-direction.
Sum up of the all previous subsections, the total actuation in the last rows of all tables represents the effort (the cost in economical side) required for restoring the shape in practical, i.e., the total actuation in all cases represents the work that has to be done in all cases of loadings. The value of necessary changing in the bar length of each member, as shown in Column 12 in all tables, denotes the role of each active member in the process of the restoration of the structure.

5. CONCLUSION

In this paper, exterior nodal displacements of the double layer dome model are examined, in which its shape configuration was distorted because of the gravity and/or lateral loading by using a relatively simple and direct method via calculating the required length actuations for controlling the shape (Saeed, 2014; Saeed and Kwan, 2016). The technique was theoretically applied to the model through MATLAB program and SAP2000 software. It can be concluded that the technique of shape adjustment is very efficient for double layer dome model, and it can roughly eliminate the displacement of definite joints (exterior joints only) by simply changing the length of certain bars by \( \varepsilon_0 \) amount. In this study, three different cases corresponding to the directions of loadings were considered. In addition, it can be also concluded that in any cases of load direction, the shape controlling can be easily accomplishing. However, a very low rate of discrepancy is observed in all cases of loading, which are 0.5%, 1.8%, and 0.02%, respectively. It also founded that the position of the actuators is the crucial in order to reach the targets with the minimum amount of actuation, which in this work was totally attained as the amount of total actuations are 874.95 mm, 246.25 mm, and 1150.8 mm in Case 1, Case 2, and Case 3, respectively. These represent the effort required for restoring the shape in practical, i.e., the total actuation in all cases represents the work that has to be done in all cases of loadings. It is determined that some of the members confirm the greater role in controlling the displaced joints as they are duplicated in Case 1, Case 2, and Case 3, and they are positioned in the inner layer of the double layer dome model. Finally, it is also concluded that the applied method for such model, the type of load, and their directions are very appropriate and applicable.

References


Digital communication has become a vital part of daily life nowadays. Many applications are using internet-based communication, and here, the importance of security rose to have secure communication between two parties to prevent unauthorized access to sensitive data. These requirements led to several studies in information security that have been done in the past two decades. Cryptography and steganography are the two main methods that are being used for information security. Cryptography refers to techniques that encrypt a message to be sent to a destination using different methods. In contrast, steganography is the science of hiding information from others using another cover message or media such as image, audio, video, and deoxyribonucleic acid (DNA) sequence. This paper proposed a new method to hide information in an image using the least significant bit (LSB) based on DNA sequence. To accomplish this, the proposed scheme used properties of the DNA sequence when codons that consist of three nucleotides are translated to proteins. The LSBs of two pixels from the image are taken to represent a codon and then translate them to protein. The secret message bits are injected into codons before the translation process, which slightly distorts the image and makes the image less suspicious and the hidden message hard to detect. The experimental results indicate the effectiveness of the proposed method with a peak signal-to-noise ratio of 57.33 at 0.7 hiding capacity.

Keywords: Image steganography, DNA sequence, Data hiding, Security, LSB.

1. INTRODUCTION

Ever since humans started to communicate with each other remotely, the need for secure communication existed, and it rapidly increases by time. The exchange of information in the internet era has led to a fast increase in the information exchange between the sender and the receiver. Even though it made life easier to send information via the internet, it suffers from a major challenge, which is secure data transfer (Comer, 2019). This is all due to the increasing number of hacking and intrusion incidents every year (Amoroso, 1999). To overcome secure communication issues, two main different methods have come to exist and have been used extensively all over the world, which include cryptography and steganography (Wayner, 2009). Cryptography and steganography are used separately (Abdo, Sabry, and A., 2018; Hussain, Wahab, Idris, Ho, and Jung, 2018). Nonetheless, they can be combined to create more robust techniques, and this makes it harder to break the security (Gupta, Ankur Goyal and Bhushan, 2012). Whereas cryptography includes techniques to encrypt a message to make it noisy data, steganography is techniques that hide a message inside a cover medium without distorting too much information on the used medium to make it less suspicious.
Abdullah et. al.: Image steganography based on DNA sequence translation properties

Different types of mediums can be used, such as image, audio, video, and DNA sequence (Cheddad, Condell, Curran, and Mc Kevitt, 2010; Djebbar, Ayad, Meraim, and Hamam, 2012; Mstafa, Elleithy, and Abdelfattah, 2017; Shiu, Ng, Fang, Lee, and Huang, 2010). Distorting medium to an extended level may give a hint to steganalysis that such medium contains a hidden message and thus may make it easier for attackers to detect the hidden message (Denemark, Boroumand, and Fridrich, 2016). Different mediums can be used alongside each other to make a more robust and less suspicious medium when hiding a message. A large number of methods have used an image for hiding information, and some researchers used DNA sequence properties to hide data inside the sequence (Shiu et al., 2010).

This paper proposed a robust information hiding method. The method uses least significant bit (LSB) of the cover image to hide data inside an image on the basis of the biological properties of the deoxyribonucleic acid (DNA) sequence with a low modification rate, which makes the cover image less suspicious to attackers. The cracking probability for the proposed method is high, which makes it hard to detect the original message.

The rest of this paper is organized as follows: Section 2 gives the reader an overview of the DNA sequence. Section 3 briefly outlines related works. Section 4 is the presentation of the proposed scheme for hiding a message. Section 5 discusses the analysis of the performance of the presented scheme. The last section has the conclusion of this paper.

2. INTRODUCTION TO DNA SEQUENCE

Understanding how the DNA works and what properties it has is essential to use it as a cover or to use its properties for data hiding. In general, DNA sequences for all living things are made up of four chemical structures, which are referred to as nucleotides. The four nucleotides are adenine (A), thymine (T), cytosine (C), and guanine (G) (Jorde, Carey, and Bamshad, 2016). In some instances, nucleotides may not be of any of these four types, which is then denoted by N as non-labeled nucleotides, and they have no role in protein synthesis (Huang, Chang, and Wu, 2014).

The aforementioned bases of DNA are essential in all biological organisms. Alignment and arrangement of the four types of nucleotides in the DNA sequence are responsible for making different types of proteins that are responsible for activities in all living organs. To make protein, DNA sequence is copied to ribonucleic acid (RNA) in a process called transcription, which is an interim process to make protein (Nussbaum, McInnes, and Willard, 2016). The process is not random but rather depends on some rules called complementary rule of DNA/RNA, and these rules depend on chemical shape and bonds of nucleotides, which consist of A-T, T-A, C-G, G-C (Yurke, Turberfield, Mills, Simmel, and Neumann, 2000). The next process that occurs to make protein is called translation, and during this process, the RNA sequence translates to an amino acid sequence, which is the base of protein synthesis (Nussbaum et al., 2016). The translation process works as follows: every three nucleotides are taken together in the RNA to make one codon, and then different codons code for different types of amino acids. Amino acids undergo multiple processes to make proteins (Jorde et al., 2016). The total number of amino acids is 20, which comes from 61 combinations of codons and three codons that do not code for amino acids and are referred to as STOP codons, which are responsible for ending sequences during the transcription process (De Silva and Ganegoda, 2016). Codons and their corresponding amino acids are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Codons list with their represented Amino acid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>AAA</td>
</tr>
<tr>
<td>CAA</td>
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</tbody>
</table>
3. RELATED WORK

Over years, many techniques have been developed for hiding information in an image as a cover medium, in which LSB-based hiding is one of the most used techniques (Nag, Choudhary, Basu, and Dawn, 2016; ur Rehman, Liao, Kulsoom, and Abbas, 2015). Even though at first the stego-message bits were directly injected to LSB of image pixels on the basis of the 24 color bits of red, green, and blue (RGB), over time, many researchers have been modifying LSB techniques especially in special domain (Hussain et al.,
Hologram of LSB has been proposed by [LSB+] firstly, and then different authors have worked on the same concept later on (Wu, Dugelay, and Cheung, 2008). The hologram was to add and change some bit to the cover image, where those bits are not from the secret message, and thus, the cover image will have modified bits that either belong to secret message or are some arbitrary bits that will make it hard for attackers and steganalysis to detect the secret message bits. Furthermore, some author has worked on only one or two colors in the spatial domain when specified conditions are met (Cheddad et al., 2010).

DNA has also been used by many researchers for data security (Leier, Richter, Banzhaf, and Rauhe, 2000; Shiu et al., 2010). DNA-based steganography is attracting researchers because of these three properties: 1- Invisibility, hiding information from steganalysis, 2- Hiding capacity, it has a reasonable size to hide message, 3- Consistency, the medium is not altered too much when hiding a message (Hafeez, Khan, and Qadir, 2014). For hiding a message in the DNA sequence, the arrangement of nucleotides is either manipulated or altered. For the ease of the process, the nucleotides are converted from English letters to binary representation, and Leier was the first one who worked on the binary representation of DNA’s nucleotides (Leier et al., 2000). Some authors (Abdo et al., 2018; Shiu et al., 2010) have worked on random nucleotides based on some mathematical models; however, altering DNA sequence to an extended level would make DNA sequence suspicious and may give some hints to attackers. Furthermore, the sequence may lose its biological functionality when converted to RNA to make proteins in the future. Hafeez (Hafeez et al., 2014) proposed a technique to hide information inside DNA sequence while preserving the sequence’s biological functionality.

4. PROPOSED SCHEME

The proposed method is based on the LSB technique to hide a secret message in a cover image medium. However, unlike the traditional LSB method in which bits of the stego message are injected directly into RGB, the proposed method injects bits of stego message to some selected colors of some pixels, even though the hiding capacity decreases; nonetheless, it makes it harder to detect the message in the cover image. To achieve this goal, the proposed method depends on the DNA sequence properties of the translation and the transcription process, which are the early stages of synthesizing proteins. Because the cover image LSBs are represented by binary for RGB and DNA’s nucleotides are represented by four English letters, a mechanism should be established to map between the two representations. Thus, the proposed method will use the binary representation of nucleotide letters according to Table 2.

<table>
<thead>
<tr>
<th>Table 2: The binary representation of nucleotides</th>
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<tbody>
<tr>
<td>Nucleotide</td>
</tr>
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<td>A</td>
</tr>
<tr>
<td>G</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>T</td>
</tr>
</tbody>
</table>

In addition to LSB for data hiding, the mapping (translation process on DNA sequence) table for amino acids is needed for the proposed method. Table 3 shows the mapping used for hiding in the proposed method. Total combinations of codons are 64 codons, which came from three letters.
A combination of the four nucleotides (four to the third power). The 64 codons are linked to 20 amino acids and the stop codons.

However, the mapping between codons and amino acids is not uniform, which means that not all amino acids have the same number of codons, and thus, some amino acids are represented by as few as one codon, whereas some are represented by as many as six codons. Nonetheless, some patterns can be found from amino acids that are making the same amino acid. Obvious patterns are for the case of two codons when representing an amino acid; they start with the same letters except for that last one, which ends with either (A and G) or (C and T). This means that whenever the A is altered to G or vice versa, the resulting amino acid will not change, the same role applies to C and T as colored blue in Table 3. For the case of four codons that represents the same amino acid, the first two letters are the same, and the third letter is the only one that changes. Irrespective of the value of the third letter, the result is always the same amino acid. The case of six codons per amino acid is nothing more than a combination of two and four cases. For the case in which only one codon represents an amino acid, nothing can be altered because the change will result in a different amino acid. The case of three codons also has two codons that can exchange letters between (A and G) or (C and T), whereas the third codon cannot be changed because it will result in a different amino acid. Codons in Table 3 are colored using three colors, where blue means only (A and G) or (C and T) can be used interchangeably to produce same amino acid, green is used for four codon that produce same amino acid, for which the last letter does not affect the resulted amino acid, and finally, red is used for codons where any change in the codon will result in a different amino acid. Two properties, which are the variance on the number of codons and the flexibility of nucleotide that can make the same amino acid, are used in this work to hide a secure message inside a cover image.

### Table 3: Codons to Amino acids exchange dictionary

<table>
<thead>
<tr>
<th>Amino acid</th>
<th>Codons</th>
</tr>
</thead>
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<tr>
<td>Lysine</td>
<td>AAA, AAG</td>
</tr>
<tr>
<td>Asparagin</td>
<td>AAC, AAT</td>
</tr>
<tr>
<td>Glutamine</td>
<td>CAA, CAG</td>
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<tr>
<td>Histidine</td>
<td>CAC, CAT</td>
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<tr>
<td>Glutamate</td>
<td>GAA, GAG</td>
</tr>
<tr>
<td>Aspartate</td>
<td>GAC, GAT</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>TAC, TAT</td>
</tr>
<tr>
<td>Cysteine</td>
<td>TGC, TGT</td>
</tr>
<tr>
<td>Phenylalanine</td>
<td>TTC, TTT</td>
</tr>
<tr>
<td>Threonine</td>
<td>AGA, AGG, ACC, ACT</td>
</tr>
<tr>
<td>Proline</td>
<td>CCA, CGG, CCC, CCT</td>
</tr>
<tr>
<td>Alanine</td>
<td>GCA, GCG, GGC, GCT</td>
</tr>
<tr>
<td>Glycine</td>
<td>GGA, GGG, GGC, GGT</td>
</tr>
<tr>
<td>Valine</td>
<td>GTA, GTG, GTC, GTT</td>
</tr>
<tr>
<td>Arginine</td>
<td>AGA, AGG, CGA, CGG, CGC, CGT</td>
</tr>
<tr>
<td>Serine</td>
<td>AGC, AGT, TCA, TCG, TCC, TCT</td>
</tr>
<tr>
<td>Leucine</td>
<td>TTA, TTG, CTA, CTG, CTC, CTT</td>
</tr>
<tr>
<td>Isoleucine</td>
<td>ATC, ATT, ATA</td>
</tr>
<tr>
<td>STOP Codons</td>
<td>TAA, TAG, TGA</td>
</tr>
</tbody>
</table>

### 4.1 Data hiding method

In the data hiding process, the LSBs of the cover image are taken to hide a message inside it. The hiding process does not directly inject the value to the LSBs but rather depends on the value of LSBs that are next to each other in image pixels. For the embedding process, each time, two pixels are taken from an image in sequential order and their LSB for RGB values are taken. This process will result in the creation of a string of six bits (R1
G1 B1 R2 G2 B2), where the R1G1B1 belongs to the first pixel and the R2G2B2 belongs to the second pixel. These six bits are converted to a three-letter codon on the basis of the binary representation from Table 2, and then, the codon value is checked against the Table 3 codons. When comparing values with codons in Table 3, three different results can be found based on the color used in the table as follows: first, when the codon value matches a red color on the table, then the value remains unchanged, and the two pixels will not be used for hiding. Second, if the value matched one of the blue colored codons, then the last bit can be used for the hiding process because according to Table 2, when the last bit is changed, the codon last letter alters from A to G and vice versa when last letter equal to A or G; otherwise, it alters from C to T and vice versa for C and T. According to Table 3, these changes will preserve the same amino acid as result. Thus, the last bit which mapped to the blue color in the second pixel is used for hiding purposes. Third, if the value of the codon matches with a green value in the Table, then the last two bits can be used for hiding since according to Table 3 the last letter green color changed to whatever possible nucleotides the resulted amino acid remains unchanged. Thus, the last two bits which are mapped to green and blue values of the second pixel are used for hiding purpose. In short, red color codons in Table 3 cannot be used for hiding, blue color codons can hide one bit and green colored codons can hide two bits. Furthermore, bits from the message that is to be hidden in the cover image is XORed with the seven most significant bits instead of directly injecting the bit into the image. The data hiding algorithm works as follows:

Data Hiding Algorithm:

Input:

M: stego message  
IMG: cover image

Output:

SIMG: image with stego message

Method:

1. Initialize the amino acid dictionary based on Table 3.
2. Convert the message M to binary message BM.
3. Take two pixels from IMG in sequential order.
4. Get values of LSBs for RGBs from the two pixels of step 3 in sequential order R1G1B1R2G2B2.
5. Map the six bits value of step 4 to three-letter combinations of nucleotides (codons) based on Table 2 which make one codon.
6. Check a match for the codon from step 5 in Table 3 and compare the value with the matched color group:
   - If the color is red, go to step 7 and continue.
   - If the color is blue, hide one bit of BM by using the XOR gate with seven most significant bits of the second pixel’s blue color.
   - If the color is green, hide two bits of BM using the XOR gate with seven most significant bits of second pixel’s green and blue colors, respectively.
7. Save the result in LSB of the corresponding Byte.
8. If BM is not empty, go to step 3. Otherwise, go to the next step.
9. Add eight bits with value zero as a stop condition and hide them as normal stego message.
10. The process is completed and the result is stego image SIMG.
The example of the data hiding scheme works as follows: suppose data type that is to be sent is text, and suppose the message is “hello.” The first thing is to convert the message to binary form using ASCII code, and thus, the binary message is equal to “01101000 01100101 01101100 01101100 01101111.” The next step is choosing an image as cover, and then the algorithm takes LSBs of RGB in sequence for the first two pixels in the cover image, suppose the value for LSBs are 011011. The next step is to convert this binary sequence to nucleotides; according to Table 2, the generated value will equal “GCT.” Then compare this sequence on Table 3 and find codons that are grouped with this sequence, if any. In the given example value, it happens to have four codons in the same group (GCA, GCG, GCC, GCT). Based on the algorithm, if the last letter has been exchanged with any other letters, then the produced codon will be in the same group. For that one letter which represents two bits can be altered using XOR logic gate. Thus, the first two bits in the binary message are taken and the last two bits in the LSB sequence are replaced with the two bits of binary message, and thus, the second pixel of cover image will be altered. The same process will continue until the whole binary message is embedded in the cover image.

Figure 1: Data hiding phase flow chart
4.2. Recovery Method

In this phase, the receiver gets the stego image that contains the hidden message that can be recovered in the reverse of the data hiding algorithm. No key needed to recover the stego message from the image. However, all procedures that have been used in the hiding algorithm should be followed, which includes binary representation of nucleotides from Table 2, mapping nucleotides from Table 3, the use of colors, number of bits for hiding process, and number of pixels that are taken each time. The algorithm for the recovery process works as follow:

Data Recovery Algorithm:

Input:

SIMG: image with stego message

Output:

M: stego message

Method:

1. Initialize the amino acid dictionary based on Table 3.

2. Take two pixels from stego image SIMG in sequence order.

3. Get values of LSBs for RGBs from the two pixels of step 3 in sequential order $R_1G_1B_1R_2G_2B_2$.

4. Map the six bits value of step 3 to three-letter combinations of nucleotides (codons) based on Table 2.

5. Check a match for the codon from step 4 in Table 3 and compare the value with the matched color group:
   - If the color is red, go to step 6 and continue.
   - If the color is blue, use the XOR gate with all eight bits of the second pixel’s blue color.
   - If the color is green, use the XOR gate with all eight bits of second pixel’s green and blue colors, respectively.

6. Concatenate the resulted bits to the BM in proper order.

7. If stop condition which is eight bits of zeros is not satisfied, go to step 2. Otherwise, go to the next step.

8. Convert the binary sequence BM to message M.

9. The recovery process is completed, and the result is the original message M.

The example of the data recovery scheme works as follows: once stego image SIMG is received, two pixels are taken at a time and the LSBs of two pixels are taken which can make six binary digits. This binary number is then mapped to corresponding nucleotides and codon base on
Table 2 and then Table 3 respectively, in the example that is given in the data hiding phase was 011011 that equivalent to “GCT.” In addition, the codon is checked in Table 3 and in our given example the “GCT” happens to have three other codons in the same group (GCA, GCC, GCG, GCT) for that two last bits are taken after XOR gate are applied of the last two corresponding colors of pixel 2. The process is repeated for the rest of the image pixels until the whole message sequence is retrieved.

5. RESULTS

The proposed scheme is tested and appraised using different standard measurements that are commonly used for steganography evaluation. For this purpose, the used measurements are hiding capacity and visual quality. As for the used tools in the proposed method, a project is developed in C# language, and a reasonable number of datasets have been tested. However, mathematical models were used, such as the likelihood probability, where each value is equally likely to appear in image LSB pixels, and thus bias is avoided when results are calculated.

5.1. Hiding Capacity

Hiding capacity refers to the number of bits from a secret message that can be embedded per pixel, and it is measured by bits per pixels (bpp) (Shiu et al., 2010). The higher the bpp, the more information can be embedded in the cover image. However, high bpp means more distortion on the cover image; therefore, maintaining the visual quality and other security measurements should be considered when the bpp increases. Even though the likelihood of bits distribution may vary from one image to another, for measurement purposes, it is assumed that all values are equally likely to appear in image LSB pixels, and thus bias is avoided when results are calculated.

For blue color, the probability is 28/64, and one bit can be embedded in the cover image. Lastly, for the green color, the probability is 32/64, where two bits can be embedded in the cover image. By calculating the probabilities, the hiding capacity is 1.438 for two pixels, based on the below equation and the bpp is 0.719.

\[ Hiding\ capacity = \frac{0 \times \frac{9}{64} + 1 \times \frac{28}{64} + 2 \times \frac{32}{64}}{2} = \frac{1.438}{2} = 0.719 \]

5.2. Visual Quality

Visual quality refers to the changes that occur in the cover image that change its quality and how much these changes are unnoticeable by human eyes; in other words, it refers to distortion or the visual modification of the cover image. The two metrics that are widely used are mean squared error (MSE) and peak signal-to-noise ratio (PSNR) (Hussain et al., 2018).

The MSE measures the error or changes between the original cover image and the cover image after embedding stego message, and it is defined as

\[ MSE = \frac{1}{H \times W} \sum_{y=1}^{W} \sum_{x=1}^{H} (IMG(x,y) - SIMG(x,y))^2 \]

where H and W are height and width, respectively, of the cover image IMG and stego image SIMG, while IMG (x,y) and SIMG (X,Y) denotes the values the pixel’s RGB of both cover and stego images with specified coordinates of height and width. The lower the MSE value, the better it is, because it means less distortion. For calculating the MSE, the assumption is that each value is equally likely to appear in the LSBs, and thus, the hiding capacity will be considered. Because there is a 50% chance that the value LSB will alter when the LSB is not equal to the stego bit, the probability of each pixel to alter roughly equal to 0.36. Therefore, the MSE for the proposed method is 0.36.
The PSNR measures the ratio between the maximum intensity value of pixel for the cover image and the MSE difference of both cover and stego images. The PSNR is an indicator to find the real visual differences between the cover and the stego image because it depends on color intensity. MSE for two images may have the same value while one image has a lower power of magnitude and the other one has a larger power of magnitude; thus, the lower magnitude power image will have more distortion even though both images have the same MSE. For that, PSNR is used, and a larger value of PSNR indicates less distortion and the quality of image maintained, which can be undetectable by human eyes. And it calculated as follow:

\[
PSNR = 10 \times \log_{10} \left( \frac{Max^2}{MSE} \right) = 10 \times \log_{10} \left( \frac{255^2}{\frac{0.36^2}{3}} \right) = 57.33
\]  

The MSE is equal to 0.36, as calculated from the MSE equation. Division by three represents the RGB colors because RGB is used instead of grayscale colors. Max is the maximum pixel color intensity, which is equal to 255. The result of the proposed method is equal to 57.33 dB, and it performs better than a number of famous methods referenced in Table 4.

The PSNR results of the proposed method compared with similar work are indicated in Table 4, and the proposed scheme has higher a PSNR with the same embedding capacity of around 0.7 bit per pixel.

<table>
<thead>
<tr>
<th>Method</th>
<th>PSNR for embedding capacity at (0.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSB++ (Ghazanfari, Ghaemmaghami, and Khosravi, 2011)</td>
<td>55.82</td>
</tr>
<tr>
<td>RHTF-based LSB (Lou and Hu, 2012)</td>
<td>55.36</td>
</tr>
<tr>
<td>RHTF-based LSB++ (Nag et al., 2016)</td>
<td>55.44</td>
</tr>
<tr>
<td>Pattern bits shuffling (Muhammad, Ahmad, Farman, and Jan, 2016)</td>
<td>~52</td>
</tr>
<tr>
<td>Proposed method</td>
<td>57.33</td>
</tr>
</tbody>
</table>

### 5.3. Cracking probability

Even though image steganography is mostly about the visualization of the image and to what extent the image has been distorted, when attackers have a suspicion about the image, then the image should have a high cracking probability to make it hard for attackers to retrieve hidden data. In short, cracking probability is the probability of attackers making a correct guess to discover a hidden message. The proposed method is simple to accomplish, yet, the cracking probability of the presented method is high. To precisely retrieve the hidden data, attackers need the following information:
First: the number of pixels used at a time, because one pixel is skipped at a time and the probability to detect that is 1/(n), where n is the number of pixels in the image.

Second: the number of bits and their position used in the XOR process is 1/(8!)

Third: the number of LSBs used in embedding process depends on the value of the LSB and can vary, having zero to two bits. In case there are no bits to hide, the probability is to check the whole image and find the four codon values that are not embedding bits, and that is 1/(n*4*(64)^2). When hiding one bit, then the probability of finding 28 codons that are used for hiding one bit and guessing its position in the pixel is 1/(n*3*(64)^28). When hiding two bits, then the probability of finding 32 codons that are used for hiding two bits and guessing their place in the pixel is 1/(n*3*(64)^32).

Fourth: to successfully guess the original message among all possible values, it requires the exponent value of the binary message length, which is 1/(2^m).

Thus the cracking probability is equal to:

\[
\text{Cracking probability} = \frac{1}{n} \times \frac{1}{8!} \times \frac{1}{n(64)^5} \times \frac{1}{n(64)^{28}} \times \frac{1}{n(64)^{32}} \times \frac{1}{2^m} \] (4)

6. CONCLUSION

In this paper, a new data hiding scheme has been proposed. Unlike traditional techniques, the proposed method is based on the biological functionality of DNA sequence and not on a mathematical model alone. The proposed method uses the translation process characteristics of DNA sequence, in which codons in the sequence are translated into amino acids. The proposed method provides an improvement over traditional LSB, and it cannot be detected easily because it does not inject the stego bits directly to all LSBs of the cover image. In addition, the distortion on the cover image is very low and is not detectable easily. The results from the PSNR and MSE are indicators of the effectiveness of the proposed method.

REFERENCES


A Study of Asphaltene Precipitation Problem in Some Wells in Kurdistan Region

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1. INTRODUCTION

Crude oil is a complex mixture of mainly hydrocarbon components. In addition, there are heteroatom compounds of sulfur, nitrogen, oxygen, and metal organic compounds within this mixture. The hydrocarbon mixture comprises components ranging from the simplest methane to the heavy wax molecules in a homogenous mixture inside the reservoir conditions of high temperature and pressure. Among these fractions, asphaltenes are considered as the most complex fraction of petroleum. They include molecules of high molecular weight and the most polar components in petroleum. At ambient conditions, they are mainly insoluble in normal paraffins such as n-heptane, n-hexane, and n-pentane but soluble in toluene or benzene. One of the most characteristic behaviors of asphaltenes is their tendency to aggregate either with other asphaltene molecules (self-association) or with resin molecules (cross-association). The deposition of asphaltenes has been identified as one of the major problems during the natural depletion of a reservoir. Its precipitation causes serious problems that cause crude oil to flow from the reservoir through the process facilities. Such problems include plugged pores, damage near the wellbore, reduced permeability and porosity, and even blocked well...
bores, which may result in enormous costs for restoration of production. Most commonly, the extent of asphaltene precipitation is associated with decline in crude oil quality and difficulties encountered in recovering crude oil. Understanding the asphaltene precipitation process and the parameters involved has therefore been a subject of interest for both the industry and scholars. The precipitation of asphaltene inside the reservoir has been reported to depend on many parameters such as change in pressure, temperature, flow rate, and composition of crude oil. However, the extent to which asphaltenes create problems by deposition is more related to their stability than to their amount in crude oil. The complex nature of asphaltenes and the way they interact with other molecules on variation in conditions such as pressure, temperature, or crude composition causes difficulties in predicting their phase behavior. In terms of composition, there are two important parameters that govern the stability of the asphaltene particles in crude oil, namely, the ratios of aromatics to saturates and resins to asphaltenes. Decreasing these ratios may cause coalescence and aggregation of asphaltene particles in the crude oil. The complexity of the crude oil composition and the reservoir condition from one side and conditions such as flow rate and change in pressure during production from the other side adds to the complexity of asphaltene precipitation from one reservoir to another. Studies have been conducted to understand the nature of asphaltene precipitation by understanding their structure and phase behavior. Simulation models have been suggested to predict the conditions at which asphaltene might precipitate, in order to take preemptive measures during production. The models suggested are mainly offered for reservoir and surface conditions. The simulation models commonly use modified equations of state (EOSs) such as the Peng-Robinson EOS (PR EOS) or the Soave-Redlich-Kwong EOS models as the framework for the intermolecular interactions and the extent to which precipitation may occur.

In the past decade, the Kurdistan region has started to produce oil from its reservoirs. There has not been much attention to the asphaltene deposition problem in the oilfields of Iraqi-Kurdistan so far. This study aimed to predict the asphaltene deposition in three oil fields by determining the crude oil composition and using the simulator program at reservoir and surface conditions.

2. MATERIALS AND METHODS

This research has used experimental data along with reservoir data to model the asphaltene precipitation at both reservoir condition and ambient surface condition. The experimental results obtained from compositional characterization and fluid behavior are used as input in the simulation program for modeling. Three wells in Kurdistan region were selected for this study, and crude oil samples were taken from these fields. For confidentiality reasons, the names and exact locations of these wells are not mentioned in this paper. Two of the three wells are located in Duhok Governorate and the third is located in Erbil Governorate. In this paper, we refer to the wells as A, B, and C. The reservoir data, as obtained from Ministry of Natural Resources, are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Reservoir and crude oil sample data from wells A–C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Reservoir pressure, Psia</td>
</tr>
<tr>
<td>Reservoir temperature, °F</td>
</tr>
<tr>
<td>Sat. pressure, Psia</td>
</tr>
<tr>
<td>Oil gravity, API</td>
</tr>
<tr>
<td>Gas to oil ratio, Scf/stb</td>
</tr>
<tr>
<td>Asphaltene (in stock tank oil), wt%</td>
</tr>
<tr>
<td>Density at reservoir T and P, g/cc</td>
</tr>
</tbody>
</table>
2.1. Experiment

The compositions of crude oil samples were determined using an Agilent series B gas chromatograph (GC). Nitrogen was used as an unretained mobile phase in these experiments. The GC was priory calibrated to determine the exact concentrations of methane up to C10+ components in the crude oil samples. A visual pressure-volume-temperature (PVT) cell (Sanchez Technologies, model FV) was used in constant mass expansion of crude oil samples. These experiments allowed determination of correct volumes of crude oil samples at selected pressure ranges.

2.2. Asphaltene modeling

Asphaltene phase behavior modeling for the selected samples was done using a software called Computer Modelling Group (CMG). Precipitation is shown using a phase behavior utility program named WinProp by CMG, which incorporates an advanced solid thermodynamic model to model the precipitation of asphaltene during depletion of a reservoir. This program can model up to three fluid phases in equilibrium with the solid. WinProp uses the Peng-Robinson EOS (1976), which is the commonly used EOS to predict the state of oil and gas phases in terms of explicit pressure.

WinProp uses EOS extensively to calculate the phase behavior of reservoir fluids. It also measures and predicts the interaction coefficients introduced to account for the interaction between unrelated molecules. The main steps required to model an asphaltene precipitation model using CMG/WinProp are as illustrated in Figure 1.

By using the outputs of the experimental work as inputs for the CMG/WinProp simulation program, an adequate asphaltene precipitation curve can be obtained to further aid this study as shown in Figure 2.
The same procedure for modeling of asphaltene phase behavior was applied for wells B and C. The results of the precipitation curves for wells B and C are shown in Figures 3 and 4, respectively.

Figure 2. Asphaltene precipitation curve for well A

Figure 3. Asphaltene precipitation curve for well B
3. EQUATION DERIVATION

Fan et al., 2002, have worked on 18 samples from different oilfields around the world and have developed a very reliable equation (colloidal instability index [CII]) that will be used and modified according to the availability of parameters in order to be best fitted with the available data from the experiment and simulation. The new equation will be named modified CII; it will suit the needs of oilfields in Kurdistan regions. The reliability of the new equation will be validated by using two methods, which is discussed in the next chapter. CII is shown in the equation below

\[
CII = \frac{S_{\text{aturated}} + A_{\text{phaltene}}}{A_{\text{romatic}} + R_{\text{esin}}} \tag{1}
\]

CII = Colloidal instability index

If CII<0.7, there will be no problem with asphaltene.

If CII>0.9, there will definitely be a problem with asphaltene. If 0.7<CII<0.9, there may be a problem with asphaltene.

First, all the parameters are in weight percent of crude oil, which means that our parameters must be in the same unit. Second, if saturate, aromatic, resin, and asphaltene (SARA) fractions are to be added together, then the result will be the original crude oil, which means that our data should represent the crude oil when added together. At this point, the only candidates for replacing SARA fractions are the components of reservoir fluids obtained from PVT analyses. Since the components in mole percentage and the sum of them equals to 100. The inputs of the equation are in line with original one, but we still need to assign each component so that it goes along with SARA constituents. Table 2 shows each component with its equivalent SARA fractions. The corresponding fractions are not real representations; instead, they are proportional to the inputs that are used in this derivation.
The basis of the classification is the definition of each constituent of SARA analysis and it is based on molecular weight. For example, asphaltenes have the highest molecular weight and aromatics have the lowest. Because there are no resins, the term has been substituted with non-hydrocarbons to account for the lost resin weight percent. Because the summation of CII inputs equals 100 and the summation of the experimental data is also 100, it is possible to manipulate our equation to give similar results with our test data. SARA analysis is performed under standard conditions but our data is from both standard and reservoir conditions. The density of the components is more in reservoir conditions than in standard conditions because of compressibility of the fluids under pressure; therefore, the conditions of CII are slightly adjusted to account for the variations in density. Density is mass per unit volume, and our equation represents the mole percentage; therefore, shifting the mole percentage of heavy hydrocarbons to the denominator would best fit the results and match better with the existing CII equation as illustrated below.

\[
\text{Modified CII} = \frac{L_c + M_c}{H_c + N_c}
\]

\(L_c = \text{Mole percentage of light hydrocarbons}\)
\(M_c = \text{Mole percentage of medium hydrocarbons}\)
\(H_c = \text{Mole percentage of heavy hydrocarbons}\)
\(N_c = \text{Mole percentage of non-hydrocarbons}\)

The steps for calculating the percentage of each component to be used in the modified CII equation are given below. The components are the results of the experimental work on the samples.

1. Calculate the mole percentage of each component (\(L_c, M_c, H_c,\) and \(N_c\)) as shown in Tables 3 and 4 for well A.

### Table 2: Hydrocarbon components with the corresponding SARA fractions

<table>
<thead>
<tr>
<th>Name</th>
<th>Components</th>
<th>Corresponding SARA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light components</td>
<td>C1–C5</td>
<td>Aromatics</td>
</tr>
<tr>
<td>Medium components</td>
<td>C6–C8</td>
<td>Saturates</td>
</tr>
<tr>
<td>Heavy components</td>
<td>C9+</td>
<td>Asphaltenes</td>
</tr>
<tr>
<td>Non-Hydrocarbons</td>
<td>CO2, N2, H2S, etc.</td>
<td>Resins</td>
</tr>
</tbody>
</table>

### Table 3: Different hydrocarbon components

<table>
<thead>
<tr>
<th>Component</th>
<th>Recombined mole %</th>
<th>Molar weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>0.316</td>
<td>28.02</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>2.073</td>
<td>44.01</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>15.354</td>
<td>34.08</td>
</tr>
<tr>
<td>Methane</td>
<td>40.986</td>
<td>16.04</td>
</tr>
<tr>
<td>Ethane</td>
<td>6.941</td>
<td>30.07</td>
</tr>
<tr>
<td>Propane</td>
<td>4.452</td>
<td>44.09</td>
</tr>
<tr>
<td>Iso-Butane</td>
<td>0.868</td>
<td>58.12</td>
</tr>
<tr>
<td>n-Butane</td>
<td>2.573</td>
<td>58.12</td>
</tr>
</tbody>
</table>

Non-Hydrocarbon components (Nc)
By applying the modified CII equation:

\[ \text{Modified CII} = \frac{Lc + Mc}{Hc + Nc} \]

Modified CII = \( \frac{58.55 + 7.794}{15.913 + 17.743} \) = 1.97

If modified CII < 0.7, there will be no problem with asphaltene.

If modified CII > 0.9, there will definitely be a problem with asphaltene.

If 0.7 < modified CII < 0.9, there may be a problem with asphaltene.

These conditions were taken from the original CII mentioned in the theoretical background of this study page 27. For wells B and C, the same procedure is performed to obtain the values of the modified CII, as follows.

Well B = 0.547
Well C = 0.545

From the results of the equation, it is clear that wells B and C will not have asphaltene-related problems during the production lifecycles. This is not the case for well A because it will eventually have problems with asphaltene during production. Meanwhile, a summary of both simulation and theoretical calculations is shown in Table 5.

### Table 4: Summation result of different hydrocarbons

<table>
<thead>
<tr>
<th>Name</th>
<th>Sum of the components (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light hydrocarbons</td>
<td>58.55</td>
</tr>
<tr>
<td>Medium hydrocarbons</td>
<td>7.794</td>
</tr>
<tr>
<td>Heavy hydrocarbons</td>
<td>15.913</td>
</tr>
<tr>
<td>Non-hydrocarbons</td>
<td>17.743</td>
</tr>
</tbody>
</table>

### Table 5: A summary of asphaltene problems in wells A, B, and C

<table>
<thead>
<tr>
<th>Well</th>
<th>At reservoir, using WinProp</th>
<th>During production, using the modified CII</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Will have problems of asphaltene precipitation</td>
<td>Will have severe problems during production</td>
</tr>
<tr>
<td>B</td>
<td>Will have problems of asphaltene precipitation</td>
<td>Will not have asphaltene problems in production tubing</td>
</tr>
<tr>
<td>C</td>
<td>Will have problems of asphaltene precipitation</td>
<td>Will not have asphaltene problems in production tubing</td>
</tr>
</tbody>
</table>
3.1. Analysis of Modified Colloidal Instability Index (MCII)

The inputs of this equation have already been established as in the original equation by using different components and grouping of the inputs. In this section, we are going to address the reliability of the MCII equation and if it can be used in other oilfields in Iraq and Kurdistan regions. For this matter, the plot of De Boer et al., 1995, will be used. De Boer and his colleagues worked on different samples around the world, both experimental and theoretical. They were able to produce a very versatile plot that is used nowadays by most scholars. First, because of the versatility of the samples in De Boers’ plot, and second, because the plot takes reservoir conditions into consideration, similar to the dataset used as input to our equation. Figure 5 shows the plot.

![De Boers’ plot for asphaltene problem prediction (De Boer et al., 1995)](image)

By using the density, reservoir pressure, and bubble point pressure for the three wells provided in the Data Collected section of this paper, a table can be constructed as shown in Table 6 and a remade version of the same is illustrated in Figure 6.

<table>
<thead>
<tr>
<th>Well</th>
<th>$P_b$ (psi)</th>
<th>$P_r$ (psi)</th>
<th>Density (g/cc)</th>
<th>$P_{reservoir} - P_{bubble}$ point</th>
<th>De Boer results</th>
<th>MCII results</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3789</td>
<td>5714.4</td>
<td>0.6521</td>
<td>1925.4</td>
<td>Upper part of possible problems into sever problems</td>
<td>Definitely have problems</td>
</tr>
<tr>
<td>B</td>
<td>395</td>
<td>5091</td>
<td>0.9025</td>
<td>4696</td>
<td>No Problems</td>
<td>No problems</td>
</tr>
<tr>
<td>C</td>
<td>390</td>
<td>5091</td>
<td>0.8929</td>
<td>4701</td>
<td>No Problems</td>
<td>No Problems</td>
</tr>
</tbody>
</table>

$P_{bubble}$: pressure at the bubble point; $P_{reservoir}$: reservoir pressure
Generally, the results from the derived equation are acceptable to an extent. The results can be replicated on other wells in the Kurdistan region.

4. DISCUSSION

The results from the experiment and modeling data are discussed to further interpret the results. First, the steps that led to the derivation of the asphaltene precipitation curve must be analyzed to conclude the credibility and reliability of the final curve. Most importantly, the curve provided by the experiment conducted in the laboratory shows the relation between the relative volume of reservoir fluids and the pressure below saturation. This curve can be correlated with the results from the regression test, both before and after regression, and it can be observed that the results from WinProp are satisfactory in the range of the experimental work done in the laboratory, as shown in Figures 8, 9, and 10 for wells A, B, and C, respectively, where the yellow curve shows the experimental work that has been inputted to the simulator and the orange line shows the initial condition of the inputted data according to the EOS. The third gray curve shows the output of the of the simulator after fine-tuning the data (regression). The regression feature in WinProp can be used to fine-tune the EOS to have a good match between the experimental work and the parameters in the EOS so that it can be used to predict accurately the phase behavior of fluids in later steps.

CONCLUSIONS

The following conclusions were observed from this study:

- The study showed a good match between experimental work and simulation. The outputs of the experimental work had been used as inputs for modeling the phase behavior of asphaltene for wells in the Kurdistan region.

- The study showed important steps and procedures required to accomplish a phase behavior model for asphaltene in wells in the Kurdistan region of Iraq by using CMGs/WinProp, which uses EOS and Nghiem for modeling asphaltene behavior. The model used data from GC and PVT analysis to model asphaltene.

- Introduction of a new screening equation called MCII used with findings from the experimental work to facilitate the
identification of asphaltene-related problems.

- The results of this model showed an acceptable range of findings and was deemed to be reliable in terms of general idea and implementation of the concept into a real-life easy-to-understand curve.

RECOMMENDATIONS

To reinforce the conclusions of this paper, further research is required in this domain, especially regarding the new screening equation.

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An Approximate Linear Analysis of Structures Using Incremental Loading of Force Method

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A B S T R A C T

A relatively simple technique has been introduced in this paper. The approach is based on the linear force method with discretization of the applied loads to the subsequent steps and updating coordinates in each iteration to have a new geometrical property. The accuracy of the technique depends on the size of the increments, which affects the number of iterations. A small change in the configuration could hugely affect the displacement and internal forces in geometrically non-linear structures, which is why the current approach is vital. The proposed technique is validated with two different techniques of non-linear analysis of the structures with a very good agreement both in terms of external nodal displacements and internal bar forces.

Keywords: Force Method, Dynamic Relaxation, Geometrically Non-linear Structures, Cable Structures, Prestressed Structures

1. INTRODUCTION

In the recent years, cable net structures have been widely constructed; they are architecturally elegant structural forms. They provide clear, large spaces such as those in retractable stadium roofs, petrol stations, and tour areas. Cable structures are the most common example of geometrically non-linear structures, as they purely behave in a non-linear way. To understand the configuration of non-linear structures after loading, a technique is presented in this work which is adopted from the linear force method.

Recently, several scholars have been studying such structures, and they have introduced Because, direct linear methods are not accurate to show the configuration of geometrically non-linear structures after loading. In this paper, two common linear methods are mentioned: The Finite Element Method and the Force Method (FM). The former provides displacements and internal forces; however, it does not give any more detail about structural behavior. Comparatively, the latter, besides the displacement and internal force, explicitly provides the states of self-stress and possible mechanisms and, last but not least, it can identify whether a structure is behaving linearly or not for a particular case of loading (Luo and Lu, 2006). This can be simply done by P.M, in which P is the load vector and M is the possible mechanism of the structure. If P.M=0, the structure is linear for the given case of loading, otherwise the structure is geometrically non-linear for the given loading. In this study, FM has been developed to analyze the non-linear structures approximately.

The approach such simple that calls no more than basic mechanics and using numerical manipulations. Thus, the technique can even be
introduced to engineering undergraduate students. This could be an easy way to introduce them to geometric non-linearity by presenting the difference in results between FM and the current technique. The layout of this paper is as follows: Section 1 is an introduction to geometrically non-linear structures. A review of previous studies has been presented in Section 2. In Section 3, development of the current technique has been explained. It is followed by an illustrative example using the proposed approach in Section 4. Section 5 contains the comparison of the current technique with other linear FM and geometrically non-linear methods in three different examples. Finally, the whole work has been concluded in Section 6.

2. LITERATURE REVIEW OR BACKGROUND

Several researchers have attempted to study geometrically non-linear structures, such as Kwan, 1998 who examined geometrically non-linear structures under loading, Coyette and Guisset, 1988 who analyzed cable network structures, and Thai and Kim, 2011 who examined pre-tensioned catenary cable element under static and dynamic loading. Similarly, the non-linear approach was also examined by Karparvarfard et al., 2015 to analyze geometrically non-linear small-scale Euler–Bernoulli beam, Stefanou et al., (1993) to analyze a saddle cable structure, and Buchholdt (1969) to study structures with finite displacements. While, different behaviors of variety of types of cable structures have been discussed in detail by Abad et al., 2013; Lewis, 2017; Naghavi Riabi and Shooshtari, 2015; Pellegrino, 1990. The basics of non-linear analysis of the geometrical non-linear structures are derived from various theories such as the second strain gradient theory (Karparvarfard et al., 2015) and the conjugate gradient method (Stefanou et al., 1993). Whereas, Kwan, 2000; Luo and Lu, 2006; Raju and Nagabhushanam, 2000 made a simple modification in linear methods to derive non-linear methods to analyze geometrically non-linear structures. While, an approximate method to solve non-linear structures was presented by Pellegrino, 1993. He divided the total load into two parts, the first part causes extensional nodal displacement and the second causes in extensional displacement.

In this paper, a linear technique has been modified to analyze linear and geometrically non-linear structures.

The advantage of this work is that FM is taught to civil engineering students, another benefit is that the technique is very simple. In order to prove the validity of the approach, the results of the proposed technique have been compared with two non-linear techniques presented by Lewis et al., 1984 and Kwan, 1998, and also with non-linear analysis of SAP2000 program software. Therefore, a brief introduction of these techniques and software are presented in the following subsections.


This approach was applied for non-linear structural analysis by Lewis et al., (1984). The method is based on D'Alembert’s principle, which is:

\[ Q(t) = [M]d'' + [C]d' + [K]d \]

(1)

This technique is famous for its accuracy to analyze geometrically non-linear structures by dealing with the structure’s motion from the beginning of loading till it settles down. \( Q(t) \) is the time dependent external load vector. The right-hand side of the formula contains three terms. The first and second parameters are \([M]d''\) and \([C]d'\) that calculate the non-linear part in which \(M\) and \(C\) are fictitious mass and damping coefficients, respectively. In addition, \(d'\) and \(d''\) are velocity and acceleration, respectively. The last parameter is \([K]d\), which is the linear part of the equation, and \(K\) is the stiffness matrix, while \(d\) is the external nodal displacement.


This technique is developed based on FM by Kwan, 1998, which has been used for analysis of non-linear structure, using the following equation:
\[ G = \frac{EA}{L_o} \Delta^3 + \frac{2t_o \Delta}{L_o} \]  

(2)

In which, \( G \) is the applied load, \( EA \) is the bar rigidity, \( L_o \) is the initial length of the bar, \( t_o \) is the pretension force in the member and \( \Delta \) is the external nodal displacement.

### 2.3. Force Method

This approach contains three main equations, which are equilibrium \( At = p \), compatibility \( Bd = e \), and flexibility \( Ft = e \) equations. where \( A \) is the equilibrium matrix, \( B \) is the compatibility matrix and \( F \) is the flexibility matrix. The technique presented in our study is based on FM; therefore, the details of FM are discussed in Section 3.

### 2.4. SAP2000

In this study, the SAP2000 software is also used for non-linear analysis of structures. In order to validate the current technique proposed in this study, which is version 20.2. The program has ability to analyze linear and non-linear structures in the sense of geometric and/or material non-linearity. Thai and Kim, 2011 utilized SAP2000 to non-linear analyze of cable structures under static and dynamic loads.

### 3. DEVELOPMENT OF THE CURRENT TECHNIQUE

The proposed technique in this study is based on FM (Kwan, 1991; Pellegrino, 1993; Pellegrino et al., 1992; Saeed, 2014; Saeed and Kwan, 2016a, 2016b) to allow “easy access” to the contributing parameters affecting the internal forces and the external displacements. The equilibrium balance between the vector of external loads \( p \) and internal bar forces \( t \) is expressed as

\[ At = p \]  

(3)

where \( B \) is the compatibility matrix, and has size \( (ij-c) \times b \). The compatibility statement of the balance of internal bar elongation \( e \) and external nodal displacements \( d \) is expressed as

\[ Bd = e \]  

(4)

The general solution \( t \) to the equilibrium equations is expressed as the sum of a particular solution (i.e., any vector \( t \) that satisfies Eq. (5), and one such vector is \( t_A \)

\[ Ft = e \]  

(5)

obtained from \( t_A = A^+p \) where \( A^+ \) is the pseudo-inverse of \( A \) and the complementary homogeneous solution (i.e., \( t \) satisfying \( At = 0 \), which is readily provided by the nullspace(\( A \))=S, and \( S \) is the states of self-stress). The total general solution is thus

\[ t = t_A + S\alpha \]  

(6)

Substitution of Eq. (6) into Eq. (5) gives

\[ e = F(t_A + S\alpha) \]  

(7)

Compatibility is imposed by imposing bar elongations \( e \) to be orthogonal to the incompatible elongations (as found in left-nullspace(\( B \)) which is identical to nullspace(\( A \)) since \( B^T = A \)). The compatibility condition is thus \( S^T e = 0 \), i.e.,

\[ S^T e_o + S^T F(t_A + S\alpha) = 0 \]  

(7)

from which

\[ -\alpha = (S^T FS)^{-1}[S^T e_o + S^T Ft_A] \]  

(8)

The expression for \( \alpha \) then reveals, by back-substitution, the structural vectors of \( e \) (Eq. (7)), \( t \) (Eq. (6)) and \( d \) (Eq. (4)).

The idea behind the current technique proposed in this work is the coordinate update of the structural geometry. The equilibrium (\( A \)), the compatibility (\( B \)), and the flexibility (\( F \)) matrices are functions of coordinates, and the change in the geometry highly affects their values. In this study, the applied load is incremental, when an increment is applied Eq. 3-8 are iteratively solved for the updated coordinates.
repeated. In each step, the output will be joint displacement and internal bar forces. While these displacements are summed to the former coordinates, the coordinates are updated and generate a new geometry. The technique is illustrated in the form of a flowchart as shown in Figure 1.

4. AN ILLUSTRATIVE EXAMPLE OF THE CURRENT TECHNIQUE

In this section, a two-bar structure has been examined using the proposed approach as shown in Figure 2. The structure has two members interconnected to each other at the mid joint, it has been supported from both ends, and $EA = 10^8 N$ for both bars. It is loaded in 10 steps in a row, in each iteration 800 N gravity load is applied to the unsupported joint. First, the structure has its original coordinates, when it is loaded, the free joint drops by 3.6477 mm; thus, new coordinates for the next step will be updated. Only the free joint will have a new position, which will be $(450, -10 + (-3.6477))$ mm. As it is clear from Table 1 and Figure 3, when the structure is loaded with the first incremental load (i.e., the first iteration) the displacement is maximum compared to the followed iterations. In other words, in each step even for the same amount of loading the displacement plunges because of the different geometry. This is due to the fact that the members experience more stress than those in the former iteration, which increases the stiffness in its yield stress range; thus, the bar elongation decreases, and this results in less displacement.

As clearly shown in Figure 1, the flowchart explains the step-by-step algorithm of how the technique works. Initial coordinates, physical properties of the structure, the maximum load, and the number of iterations should be inputted. The necessary manipulation is performed including applying the incremented load and then the displacement is obtained until the number of iterations are reached. Finally, the loop stops and the cumulative displacement is obtained.

![Figure 1. Flowchart of the current technique.](image-url)

Figure 4 shows that the accuracy of the technique is proportional to the number of iterations. In other words, the precision of the approach is enhanced by minimizing the load increments. As it is clear from the figure the result gets closer and closer to the results of Dynamic Relaxation when the number of iterations is increased. In this
example with applying only 10 load increments, the results have a very good agreement with non-linear technique of analysis (Dynamic Relaxation). Numerically speaking, when FM is used (i.e. number of iterations is one) the displacement of the free joint is $-36.466$ mm as shown in the labeled line of Figure 4. While, for two iterations, the displacement rested at $-20.5375$ mm and so on when the number of iterations is 10 the displacement is $-13.5421$ mm which is very close to the exact geometrically non-linear analysis method Dynamic Relaxation which gives $-11.1168$ mm.

**Figure 2.** Structure 1, the two-bar geometrically non-linear structure. J1 and J3 are in the same level but J2 is 10 mm bellow J1

**Figure 3.** Structure 1 configuration in 10 iterations

<table>
<thead>
<tr>
<th>Table 1: The components that are used in the project</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong></td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Iterations</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>
5. RESULTS and DISCUSSION

In this section a detailed comparison of the results of the current technique and the quoted methods for the structure examined in Section 4 and two other structures have been presented.

5.1. Structure 1

The properties of this structure have been detailed in Section 4 and the structure's geometry is shown in Figure 2. It can be clearly seen from Table 2 that there is a substantial discrepancy of the vertical displacement of J2 between FM and the approved techniques, the dissimilarity is about 228%.

Whereas the difference of the results of the current approach with the quoted methods is around 16%. It can be said that the geometry of the geometrically non-linear structures is highly significant. Direct linear methods are deficient for such structures that is why this new technique is essential. In this method the applied load is discretized to number of iterations, this leads to reduction of sensitivity of the structure to the load, because the load is applied incrementally. The results of the internal loadings also have good relations with the non-linear
techniques as compared to the results from linear FM.

Table 2: Comparison of the Current Technique with the Other Methods in Terms of Displacement and Internal Force for Structure 1

<table>
<thead>
<tr>
<th></th>
<th>FM</th>
<th>Current Study</th>
<th>Kwan</th>
<th>Lewis</th>
<th>SAP2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical displacement</td>
<td>Joint 2</td>
<td>−36.4770</td>
<td>−12.9887</td>
<td>−11.1120</td>
<td>−11.1168</td>
</tr>
<tr>
<td>Internal Force (N)</td>
<td>Bar 1</td>
<td>180040</td>
<td>104580</td>
<td>85303</td>
<td>85334</td>
</tr>
<tr>
<td></td>
<td>Bar 2</td>
<td>180040</td>
<td>104580</td>
<td>85303</td>
<td>85334</td>
</tr>
</tbody>
</table>

5.2. Structure 2

In this example, a three-dimensional structure is studied as shown in Figure 5, simply two other members were connected to the mid joint of the structure 1 from out of plain direction and the load has been doubled as presented in the figure. This has been performed to test the technique with three-dimension structures and to see whether the results match with the results of structure 1. The properties are unchanged; the unsupported joint is subjected to 16,000 N downward. As one sees the results from Table 3, there is no amendment in the sense of the amount of displacement and internal forces. It can be said that the technique is also applicable to analyze three-dimensional structures.

5.3. Structure 3

An eight-bar truss see Figure 5 has been examined using FM, the current study and the two quoted non-linear approaches. This structure is predicted to behave linearly because it is made out of steel; thus, it is not a cable structure, 1400 kN downward has been applied to the far joint to get a noticeable displacement. This is done to see the precision of the current study to analyze linear structures. The structure has five joints and eight bars with $EA= 200,000 \times [650 \ 750 \ 500 \ 500 \ 750 \ 500 \ 650 \ 650]$, respectively based on the bars’ number. In this example number of iterations is 100. Table 4 clearly shows that the results of the current technique are closer to the quoted exact methods than the FM method. The discrepancy between FM and the approved non-linear methods is just above 3.5% whereas the dissimilarity between the current technique and the non-linear methods is just under 1.7%.

Figure 5. Structure 3, a linear and determinate truss with eight members
6. CONCLUSION

A relatively simple and approximate method is proposed in this study, which is accurate to solve linear structures and effectual to analyze both two and three-dimensional geometrically non-linear structures. However, the degree of accuracy depends on the number of iterations and the precision is proportional to the number of iterations. Besides the lack of complications, the proposed technique has been proved to be very simple and efficient compared to ordinary linear methods given the results of the proposed method are comparatively close to the established non-linear techniques in its accuracy of solution.

REFERENCES


1. INTRODUCTION

Strengthening and retrofitting structures is one of the essential steps to reduce damage. For instance, in order to reduce earthquake induced damages, which is an integral part of natural disasters, fundamental planning is needed. Experience has proven that even weak earthquakes have destructive effects on historical structures. Strengthening involves increasing the seismic capacity of existing buildings. The seismic behavior of existing buildings is affected by the inadequacy of the main structure, the strength loss of old materials, and the exhaustion of bearing elements during the lifetime of the building. Therefore, retrofitting of damaged and undamaged buildings is an urgent need. Strengthening is not possible without analysis and engineering calculations and doing numerous experiments (Fischetti, 2009).

**ABSTRACT**

The history of each country is the identity of its people, and the preservation of originality and culture is considered a social value. Moreover, the maintenance of valuable buildings that reflect the path to the growth of human civilization is of particular importance. To achieve various goals, including the development of the tourism industry, each country tries to prevent the destruction of historic buildings, or to resuscitate them by applying various methods of restoration and retrofitting. Iran being an ancient civilization has many valuable historical buildings. Traditional construction materials included masonry materials such as clay and mud, stone, wood, and brick. Because of the weakness in physical structure and a lack of allowable shear and tension strength, those heritage structures are susceptible to strong forces such as earthquakes. Studies on historical sites and heritage complexes in Iran, indicate no fundamental work has been done in this regard, and practically measures have been taken without any improvement in the structural performance of the buildings. To minimize the damage on historical buildings to the least possible extent, the seismic behavior of such buildings against the seismic forces could be enhanced through special strengthening techniques. This paper is the result of the desk research using descriptive-analytic method, which includes classifying the main elements of historical building’s structure, their possible weaknesses, and a review of reinforcement and restoration resolve methods for each structure.

Keywords: Seismic Retrofitting, Cultural Heritage Structures, Strengthening Methods, Traditional Masonry Structure
The three main features that increase the vulnerability of historical buildings to natural disasters such as earthquakes include the following: exhaustion of the material, low-strength material, and structure heaviness; accordingly, the solutions to protect these buildings against earthquake should be in the direction of eliminating these shortcomings.

2. FACTORS AFFECTING THE DETERMINATION OF SEISMIC RETROFITTING METHODS OF HISTORIC BUILDINGS

Considering the climatic conditions of Iran, most of the historical buildings are made of mud, brick, or traditional masonry materials. Thus, studying the behavior type of such buildings against earthquake Considering the climatic conditions of Iran, most of the historical buildings are made of mud, brick, or traditional masonry materials. Thus, studying the behavior type of such buildings against earthquake forces and the amount of resistance and ductility of materials used in them can be influential in selecting an appropriate seismic retrofitting method. In most structures, there are no resisting elements against the earthquake forces. Generally, in order to study the seismic retrofitting of historical buildings, the following fundamental points can be noted (Molaei et al. 2014).

2.1. Structural System

Historical structures suffer from heavy losses owing to the lack of a complete transmission path, irregularity in the plan, the insufficient shear strength of the walls, the lack of coordination of structural elements, and, ultimately, the lack of a proper foundation (Afshari, 2017; Code No.360, 2007).

The main weakness of these structures against earthquake loads is the lack of ductility, which decreases the absorption of earthquake forces in comparison with ductile structures. In the case of continued seismic loads, the main bearing elements of the building suffer serious structural damages. The masonry materials used in the historical buildings are often fragile and non-ductile, and the used mortars such as lime mud cause poor adhesion between the mudbrick pieces, and the earthquake induced lateral forces produce shear and bending forces in brick and mudbrick walls. The forces cause the layers to move on each other owing to the weak bond between the rows and ultimately result in failure in the walls (Chavoshan et al. 2012; Afshari, 2017).

2.2. Walls

Strengthening a masonry building should be considered thoroughly. In all the strengthening methods, increasing the strength of outer walls, which have not much resistance against lateral loads because of the lack of ductility, is taken into consideration (Vaisi, 2011).

2.2.1. Brick Wall Failure Modes

The failure modes of a separated brick wall are divided into two main groups of in-plane and out-of-plane failures. In the case of in-plane failure that the wall is subjected to a high vertical load and the wall height to length ratio is less than one, the shear failure mode occurs. Moreover, if the height to length ratio is greater than one (approximately equal to 2) and the vertical load is too high, there is still the possibility of shear failure. If the shear strength of the wall is small and the lateral load is large in comparison to the vertical load, then sliding shear failure will occur. In this case, the wall height to length ratio is usually less than 1.5 to 1 and about 1 to 1. If the shear strength of the wall is sufficient and the column height to length ratio is 2 to 1, then flexural failure occurs (Tayefi Nasrabadi et al. 2008).
Historical buildings are constructed with materials and techniques resistant to compressive forces and do not have the proper resistance against shear and flexural stresses. Therefore, the insufficient resistance of historical buildings to lateral loads will lead in collapsing of such historic monuments (Afshari, 2017).

2.3. Ceiling Systems
The main imperfections and weaknesses in the roofs of such buildings are (Code No.360, 2007):
1. Heavy-weight ceilings.
2. Lack of uniformity and coherence in the ceilings.
3. Lack of proper connection between the ceiling and the walls.
4. Lack of adequate strength rigidity in flat ceilings.
5. Inappropriate restraining of arched and domed roofs against the drift.

2.4. Foundation Systems
The main imperfections in the foundations of such buildings include (Code No.360, 2007):
1. Non-uniform foundation settlement.
2. Erosion of foundation soil over time.
3. Lack of uniformity and coherence in the foundation.

3. IMPLEMENTATION METHODS FOR SEISMIC RETROFITTING OF VALUABLE HISTORICAL BUILDINGS

3.1. Walls (Increased ductility and load-bearing capacity)

3.1.1. Steel mesh and shotcrete method
In this method, the wall plasterworks are destroyed and removed up to the surface of the brick so that the wall surface is free of materials such as plaster and harmful substances for concrete. Flooring at the foot of the walls is also removed until the bottom of the wall (tie-beam) is reached. Then, rebars are placed in the tie-beam with specified and certain intervals and the wall meshing is performed. After that, the concrete is sprayed with a minimum thickness of 3 cm. The wall surface is processed again (Tayefi Nasrabadi et al., 2008; Ghiassi et al., 2011)
Advantages (Tayefi Nasrabadi et al. 2008):

- The method is well-known and applicable on walls.
- It occupies a small space beneath the building.
- It makes no changes in the building architecture.
- Almost uniform stiffness is distributed at the building.

Disadvantages (Tayefi Nasrabadi et al. 2008):

- The wall plaster must be completely removed.
- The implementation is prolonged owing to destruction and thinner re-execution of plasterworks.
- Inability to exploit the building during retrofitting operations.
- It requires special equipment for doing shotcrete operation.

3.1.2. Grouting

Grouting is one of the most effective and economic solutions for increasing the shear and flexural strength of old and historical buildings. Through Grouting, it can be penetrated into the structure components without damage and destruction, and by injecting expanding cements and epoxy resins, the cohesion and integrity of the structural elements can be increased. Mortars used to connect mudbrick and brick walls are lime mud or sometimes mud types that have no
resistance to earthquake induced tensile and shear forces. Therefore, the mortar between brick layers (rows) is removed using special grinders and the grooves created are rinsed thoroughly with water and then, special epoxy adhesive is injected inside the rows. The epoxy adhesion increases the shear and flexural strength of the wall against earthquake lateral forces (Afshari, 2017).

Figure 3. Increasing the shear and flexural strength of a brick wall with grouting (Afshari, 2017)

3.1.3. The use of high-strength fiber reinforced polymers

New materials that have made a fundamental change in retrofitting of building are included fiber reinforced polymers (FRPs). FRPs consist of high-strength fibers in a resin matrix. These fibers can be made of carbon (CFRP), glass (GFRP) or aramid (AFRP). The tensile strength of this fiber in a longitudinal direction is several times that of steel.

In addition to having high tensile strengths, FRP has two other advantages, including:

Light weight and durability in different environmental conditions makes it possible to retrofit historical buildings. FRPs can be produced in a variety of shapes such as plate, strip, rebar, and mesh. One of the most effective and simple methods is using FRPs on external surfaces of structural elements, such as walls. These fibers used in various structural elements because they are easy to use and have high flexibility. The use of FRP in different elements and connection points, such as the connection of walls can significantly increase the bearing capacity and the ductile behavior in historical masonry buildings.
In 2007, the experts of this industry studied the latest achievements at London city. One of the important conclusions of this conference was to identify the high potential of these fibers for being used in the retrofitting of historical structures. Today, the use of FRP method for reparation and retrofitting is taken into consideration throughout the world. [3] In repairing historical buildings, the use of FRP may have most advantages and the least loss on the beauty of that texture. However, its behavior has not been tested over long time under different temperature and humidity conditions, and further research is needed. The seismic analysis of unreinforced masonry structures is a new topic. Most experts emphasize that masonry structures are not of adequate flexibility to resist earthquakes (Jalilian et al., 2011).

**Advantages** (Chavoshan et al., 2012; Jalilian et al., 2011):

- It occupies a small space beneath the building.
- It makes no changes in the building architecture.
- High strength and stiffness to weight ratio.
- Design flexibility.

**Disadvantages** (Vaisi, 2011):

- The wall plaster must be completely removed.
- Very high cost of raw materials.
- Need for high technology for implementation.

### 3.1.4. Reinforcing the walls

One of the methods of repairing and retrofitting of the structural elements of the historical buildings is the injection of expanding cement grouts or special epoxy resins inside the pores formed between the structural components. In this case, the injecting material fills the holes and pores between the masonry materials and causes uniform distribution of stresses between the various components of the structure. The lateral bearing capacity of the building increases with increasing the flexural and shear strength of the used materials. Of course, using this method in combination with other techniques, such as grouting, can be more effective. In historical buildings, to retrofit mudbrick and brick walls, the pores inside the walls are first filled with expanding cement grout, and, in the second stage, the adhesion of the mortar and its cohesion to the old materials are strengthened by injection of epoxy resin inside the wall rows (Afshari, 2017).

**Advantages** (Vaisi, 2011):

- Keeping the originality of the building considering enhancing the quality of the

---

**Figure 4.** Application of CFRP/GFRP on building, wall and column (Meireles et al., 2013)
main materials.
- Minimizing damages and manipulation of architectural coverage.

**Disadvantages** (Vaisi, 2011):
- Need for high technology for implementation.
- Need for doing tests after grouting to ensure the performance.

### 3.1.5 Embedding concrete and steel structural elements inside the long walls (Invisible form)

Sometimes, in many historical structures, such as citadels, forts, and castles, there are very high and long mudbrick walls that surround the building’s area. They have a large thickness without lateral restraint and are overturned because of the non-tolerable earthquake lateral forces (perpendicular to the wall). In order to prevent the overturning of these walls, it is possible to put concrete or steel columns in their webs according to the position and the material of the wall and in the end, all the evidence of retrofitting can be modified using the previous coating without significant change in the apparent quality of the building (Afshari, 2017; Mohebali et al., 2014).

![Figure 5. Embedding steel structural elements inside the wall "invisible form" (Mohebali et al., 2014)](image)

**Advantages** (Vaisi, 2011):
- Ease of implementation owing to the presence of useless and hidden spaces, including wind catcher.

**Disadvantages** (Vaisi, 2011):
- Impossible to assure appropriate interaction of old and new elements.
- The implementation time is prolonged because of destroying and rebuilding plasterwork.

### 3.1.6 Using seismic damper inside walls

The dampers are a seismic bracing system in buildings and bridges that act only against the various vibrations caused by earthquake and do not play any role in bearing static loads. This makes it easier to predict the behavior of a structure under seismic loading. While usually materials can provide critical damping of about 5%, by using seismic dampers along with lateral bearing elements or structural joints, we will be able to increase the damping of the structure by more than 50%, which means a significant amount of dissipation in the earthquake load. Adding dampers, is considered as a rather unusual strategy for seismic retrofitting. Adding dampers reduces the overall displacement of the structure, response acceleration, and the lateral displacement of the interior floor, which will be associated with rescuing structural and non-
structural damages. Moreover, the architectural problems in the design of buildings is reduced (Meireles et al., 2013).

**Advantages** (Vaisi, 2011):
- Reducing force exerted on the wall and preventing failure,
- No need for replacement after the earthquake event.

**Disadvantages** (Vaisi, 2011):
- The necessity of existing column or vertical column-tie connected to it
- Destroying the wall in order to embed the dampers.

### 3.2 Ceilings, portal, and domes

In this section, practical solutions for the retrofitting and strengthening of wooden ceilings and barrel vault are presented, by applying which, the strength and stiffness of the ceilings and their rigidity against the lateral forces of the earthquake can be increased. Improvement of ceilings in general is performed by considering the following basic principles (Tayefi Nasrabadi et al. 2008).

#### 3.2.1. Reducing Ceiling Weight

Wooden ceilings: In these ceilings, a relatively thick layer of thatch plaster is used to seal the ceiling, and it is usually used from a new thatch plaster layer to re-insulate the previous layers that increases the weight of the ceiling. To reduce the ceiling weight, one of the following solutions can be used: The soil and the thatch are first removed from the ceiling and after placing a wooden plate on the ceiling main beams, the created surface is used as mold and thin a layer of reinforced concrete (having a thickness of 5 cm) is implemented on it that is connected to the walls (Tayefi and Nasrabadi et al. 2008).

![Figure 6. The reducing wooden ceilings weight with a cooperating reinforced concrete slab (Meireles et al., 2013)](image)

3.2.1.2. **Barrel-vault ceilings**: In this type of roof, owing to the arched brick vault, the roof uses a lot of heavy materials for filling and flooring, including soil brick. It is possible to reduce the floor weight by replacing these with mineral pumice or concrete foam in the flattening (Tayefi Nasrabadi et al. 2008).

3.2.2. **Increasing Rigidity of the Ceilings**

Flat ceilings are one of the most important and effective elements of the structural members that play the most role in absorbing and distributing earthquake lateral forces between the vertical elements of the structure. The ceilings of historical buildings are mostly barrel vault, wooden beam, and dome or arch ceilings, which owing to insufficient rigidity cannot absorb seismic forces from the earthquake and suffer heavy damage in severe ground motions.
Therefore, to increase the rigidity of the ceilings, we must (Afshari, 2017):

- Remove the entire loads accumulated over the ceiling.
- Implement a two-sided rebar mesh on the ceiling with a maximum mesh size of 50 cm and rebar of size 12 mm in diameter.
- Implement concrete tie at the four sides of the ceiling, in such a form that the rebar meshes are placed inside it.
- Implement a 5-cm layer of concrete on the barrel-vault ceiling.

![Figure 7. Typical detail of increasing rigidity of the ceilings (Afshari, 2017)](image-url)

3.2.3. Appropriate connection of ceiling to wall
A major drawback of the structure of this type of buildings is the lack of adequate connection between the components of the structural elements. One of the main weaknesses is connection of ceiling to wall (Afshari, 2017).

3.2.3.1. Reinforcing the connections of several types of traditional ceilings to wall

- **Wooden ceilings**: The connection of the wooden ceiling to the walls is carried out by steel restraints. In this case, the main beams of the roof are nailed or screwed into steel straps, and the straps are restrained to other steel plates behind the wall using screws after passing through the wall thickness (Tayefi Nasrabadi et al., 2008).

- **Barrel-vault ceilings**: To strengthen the connection of vertical walls to the ceiling, before pouring the reinforcing concrete into the ceiling, several holes with at least 50 cm in height should be constructed vertically on the wall at a maximum intervals of 30 cm and vertical rebars of no.14 should be embedded in them using epoxy resins or expanding grouts. The free end of the rebars, which are placed inside the collar (beam-tie) around the ceiling, should be bent at an angle of 90° and inserted to a length of 50 cm inside the reinforcement of the ceiling, and then the ceilings and coils are simultaneously concreted (Afshari, 2017).

**Barrel-vault roof (portal)**: To eliminate the thrust forces in a portal, steel packing operation is performed (using concrete, wood, steel profile), which is performed in the following stages (Mohebali et al., 2014):

- First, precaution, protection, and shoring operations and the elimination of danger are carried out in the building.
- Digging the foundation and material separation should be done under the supervision of experts, so that the historical layers and the main foundation are not damaged.
- Because these tensile materials must be hidden (hidden steel), it is necessary to
examine the location of the materials before embedding them, and the materials used should be carefully numbered and removed, so that after performing the operations, they are exactly installed in their original location in such a way that there is no significant change in the appearance of the building at the end.

Figure 8. An example of the reinforcement of a portal with steel packing (Mohebali et al., 2014)

**Strengthening of domes**: The use of materials with expanding property is a very good choice for pre-stress strengthening in historical buildings. Because not only do they structurally reduce the tension, deformation, and, finally, the cracks in the masonry structure by creating a uniform pre-stress, but their use is consistent with the rules of restoration of the historical structures in terms of minimizing manipulation in the building. By injection of these materials into the gaps of the mortar in areas of the dome where tensile cracks exist, it is possible to avoid expansion of the cracks and creating new cracks in the dome, and thus strengthen the dome against the vibrations from earthquakes and any other loads that can lead to create tensile stresses (Sahab et al. 2011).

**3.3. Foundation**

Foundation is one of the most effective and important elements in the path of complete transmission of earthquake lateral loads that play the main role in earthquake energy absorption and transfer it to the structure. Therefore, it is expected to give it special attention in the retrofitting and strengthening of historical buildings. Because of their old age, the foundations of historical buildings are usually made of lime concrete with rock, which is relatively good against compressive forces, however the soil beneath foundation that is composed of various types such as alluvial, clay, gravel, and sandy soil, are getting compacted and settled under stresses caused by seismic loads and the heavy structure and eventually causes an asymmetric and heterogeneous subsidence of the building. The subsidence causes heavy damages to historical and old buildings. So, using different injection methods, the soil density under the foundation should be increased significantly and, finally, by increasing the compressive and shear strengths, it should be able to overcome the pressures caused by the earthquake dynamic loads and the heavy weight of the building (Afshari, 2017)
3.3.1. Injecting concrete below the foundation

The drills that are inserted into the ground by impact are guided below the foundation, and a mixer is used in order to homogenize the grout fluid during injection. After blending water and cement with the ratio of 1:2 in the mixer, the cement grout is injected through special hoses into the hole. The injection process continues to 5 atm, and owing to the pressure, the grout enters the soil pores under the foundation and combines with sand and soil grains, forming an integrated resistant body. The compressive and shear strengths of the foundation are increased because of the increase in the soil and the foundation becomes able to resist the pressures from seismic loads, without subsidence (Afshari, 2017).

Figure 9. Underpinning - Injecting a grout mixture into the sub soil under the weak foundation (Ghiassi et al., 2011)

4. Conclusion

Valuable historical buildings and cultural heritage have to be preserved regarding their cultural and historical value. The compressive strength of the building materials in such structures are much higher than their tensile strength. In this paper, attempts were made to review a number of conventional methods, in which attention is paid to the most important issue in the maintenance of historical monuments, including the preservation of the totality of the building and the exterior and interior views without excessive disturbance. These retrofitting techniques improve strength properties of old structures by:

- Increasing building ductility.
- Increasing integrity of the elements
- Completion of the load transferring process to the foundation.

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The Darbendi-Bazian-Abandoned Alluvial Fan: An Indication for the Lateral Growth of Qara Dagh Anticline, SW Sulaimani, Kurdistan Region, NE Iraq

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1. INTRODUCTION

Alluvial fans are formed by dropping of the solid materials carried by water either due to decrease of gradient of a stream or a drop in local base level (Bull, 1991). As this reduces the capacity of the channel, the feeder channel will change direction over time, gradually building up a slightly mounded or shallow fan shape. Therefore, the sediments of any alluvial fan are usually poorly sorted. “The fan shape can also be explained with a thermodynamic justification: the system of the sediment introduced at the apex of the fan will trend to a state, which minimizes the sum of the transport energy involved in moving the sediment and the gravitational potential of the material in the cone” (American Geological Institute, 1962). At the apex of the fan which represents the discharge point there will be iso-transport energy lines forming concentric arcs. Thus, the materials will tend to be deposited equally about these lines, forming the characteristic cone shape (Baker et al., 2015). Different authors have discussed the role of the climate in the formation of alluvial fans (Dorn, 2009). Majority of authors believe that the
climatic changes influence the weathering, stream flow, mass movements, and sediment supply in the drainage basin above the fan, as well as the gullying and soil development on fan deposits, besides the base level of a closed basin. Therefore, the role of the climate in formation of alluvial fans is essential, and it is one of the main and major factors that play role in their formation.

1.1. Study Area

The study area is located in Sulaimani Governorate at Darbendi Bazian, near Takya town within the Iraqi Kurdistan Region (Fig. 1). The main road between Kirkuk and Sulaimani cities crosses the fan longitudinally from SW to NE. The coordinates of the studied 6 sections are shown in Table (1).

![Figure 1: Satellite image showing the location of Darbendi Bazian alluvial fan and the studied six stations](image)

<table>
<thead>
<tr>
<th>Table 1: Coordinates of the six studied sections</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section No</strong></td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>
1.2. Aim

This study aims to prove the existence of an abandoned alluvial fan called the Darbendi Bazian alluvial fan in this study. Moreover, to prove that the fan was abandoned owing to Neotectonic activity, which indicates the lateral growth of Qara Dagh anticline and that Tinal stream was the feeder channel of the fan and nowadays it is flowing in a reverse direction and crosses Qara Dagh anticline at Bassara gorge.

1.3. Previous Works

The following studies were carried out near the study area:

Sissakian (2010) studied the Neotectonic evidences at Darbendi Bazian vicinity and along Qara Dagh anticline. Sissakian and Abdul Jab’bar (2010) studied many transversal gorges in Iraqi Kurdistan Region; among them is Darbendi Bazian gorge, they mentioned it is a wind gap. Al-Kubaisi and Abdul Jab’bar (2015) studied the lateral growth of Qara Dagh anticline from which Darbendi Bazian alluvial fan is originated and concluded that Qara Dagh anticline consists of six segments. Sissakian et al. (2018) studied Qara Dagh anticline and proved it consists of six segments that are growing and are conjugated together.

1.4 Materials and Methods

To fulfill the aims of this study, the following materials were used:

- Geological maps at a scale of 1:100000 and 1:250000,
- Topographic map at a scale of 1:100000,
- Sentinel-2 Satellite images of 80 m resolution,
- Reviewing relevant published articles and books that deal with the development of alluvial fans.

The geological and topographical maps with the satellite images were used to study, measure, and interpret visually the dimensions, shape, and characters of Darbendi Bazian alluvial fan. Field work was carried out to check the interpreted data, describe the sediments of the fan from the existing exposures along the limits of the fan and some hand dug water wells. The size, shape, and roundness of the pebbles are measured and/or indicated. Moreover, to make relevant documentary photos for features that prove the existence of the fan.

2. GEOLOGICAL SETTING

The geological setting of the study area is briefed hereinafter depending on the best available geological data. The geomorphology, tectonics and structural geology, and stratigraphy of the study area are mentioned depending on Sissakian et al. (2014), Fouad (2012) and Sissakian and Al-Jiburi (2014).

2.1. Geomorphology

The study area is located physiographically between the High Mountain Province and Low Mountains Province (Sissakian and Fouad, 2012). The main geomorphological units are:

- **Structural Unit:** The main forms are the anticlinal ridges along the southwestern limb of Qara Dagh anticline (Fig. 2).
- **Alluvial Unit:** The main forms are the alluvial fans (Fig. 1) that are well developed along the southwestern limb of Qara Dagh anticline (Fig. 2).
- **Structural Denudational Unit:** The main form is the flat irons that are well developed along the southwestern limb of Qara Dagh anticline within the Pila Spi and Fatha formations (Fig.3).

2.2. Tectonics and Structural Geology
Darbendi Bazian alluvial fan is located mainly in the Low Folded Zone; whereas, the apex of the fan is located in the High Folded Zone (Sissakian and Fouad, 2012). Both zones are located within the Outer Platform (Unstable Shelf) of the Arabian Plate (Fouad, 2012). Moreover, both zones belong to the Zagros Fold – Thrust Belt (Berberian, 1995; Alavi, 2004 and Fouad, 2012). The alluvial fan had originated from a large water gap that was developed within the southwestern limb of Qara Dagh anticline, which is a long and narrow NW – SE trending anticline consisting of six segments of double-plunging anticlines (Sissakian et al., 2018).
2.3. Stratigraphy

Darbendi Bazian alluvial fan is originated from the Pila Spi Formation and lay on many other formations. All those formations are mentioned very briefly depending on Sissakian and Al-Jibury (2014) and Sissakian and Fouad (2012 and 2014).

- **Pila Spi Formation** (Upper Eocene): Consists of well-bedded dolostone and limestone with rare marl intercalations. The thickness of the formations is about 120 m.

- **Fatha Formation** (Middle Miocene): Consists of a reddish-brown claystone with few beds of hard light-gray limestone and hard gray and white gypsum. The thickness is 100 m.

- **Injana Formation** (Upper Miocene): Consists of cyclic alternations of reddish-brown well-bedded hard sandstone and reddish-brown fairly hard claystone (Fig. 4). The thickness is 120 m.

- **Mukdadiya Formation** (Upper Miocene – Pliocene): Consists of cyclic alternations of gray well-bedded fairly hard and friable sandstone and gray fairly hard claystone; some of the sandstone beds are pebbly. The thickness is 400 m.

- **Bai Hassan Formation** (Pliocene – Pleistocene): Consists of conglomerate, reddish-brown sandstone, siltstone, and claystone, in cyclic nature, the thickness is about 500 m.

- **Alluvial Fans** (Pleistocene): Besides Darbendi Bazian alluvial fan, many small fans are developed on both sides of the main fan (Figs. 1 and 3). The constituents of the fans are mainly pebbles and fragments of dolostone and limestone derived from the Pila Spi Formation, well cemented by reddish-brown clayey materials (Fig. 5). The thickness of the fan sediments as seen from the investigated exposures ranges from (2.5 – 6) m.

*Figure 4: Exposure of the Injana Formation, note the reworked carbonate fragments and pebbles derived from Darbendi Bazian alluvial fan.*
3. DARBENDI BAZIAN ALLUVIAL FAN

3.1. Characteristics

Darbendi Bazian alluvial fan is an abandoned fan derived from Darbendi Bazian gorge located at Qara Dagh Mountain. According to alluvial fans classification of Sissakian and Abdul Jab’bar (2014) in Iraq, the Darbendi Bazian alluvial fan is single stage, medium sized, and top covered by soil. No stages were recognized neither from visual interpretation of the satellite images nor during the field investigation. The length and maximum width of the alluvial fan are 4.18 km and 1.35 km, respectively. The height of the apex is 934 m (a.s.l.); whereas, the toe area is 835 m (a.s.l.). Accordingly, the gradient of the fan will be 2.34%, which is about 3°. This gradient is within the usual gradients and/or slopes that are usually less than 10° (Bull, 1991). The fan’s concave shape is lost because of farming activities and because it is a residential area occupied by Takya town (Figs. 1 and 3).

To indicate the changes in the constituents of Darbendi Bazian alluvial fan including pebble size, roundness, and type, 6 stations were investigated (Fig. 1), the results are presented in Table (2). No filed data were recognized about the "bar and swale" micro-topography, within the alluvial fan. The authors believe the range is around (0.5 – 3) m.

In the study area, Qashlagh and Hanjira Mountains that are parts of Qara Dagh main Chain (Range) and are located on the west and east of Darbendi Bazian gorge are the source area for formation of the alluvial fan; they form elongated mountain chains with a maximum height of 1440 m (a.s.l.), almost with rare vegetation cover, forming the range topography. Whereas, Takya Plain is the depositional basin in which the alluvial fans are formed. Therefore, the "basin-and-range topography" is typically formed in the study area.
Table 2: The description of the studied stations in Darbendi Bazian alluvial fan

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Location</th>
<th>Thickness of the fan deposits (m)</th>
<th>Pebble Size (cm)</th>
<th>Pebble Shape</th>
<th>Pebble Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Apex</td>
<td>6</td>
<td>4 – 25</td>
<td>SR, SA</td>
<td>Limestone</td>
<td>Partly cemented by reddish-brown clayey material.</td>
</tr>
<tr>
<td>2</td>
<td>Upper western part</td>
<td>2</td>
<td>4 – 16</td>
<td>R, SR</td>
<td>Limestone</td>
<td>Partly cemented by reddish-brown clayey material, pebbles coarsening upwards.</td>
</tr>
<tr>
<td>3</td>
<td>Distal part</td>
<td>3</td>
<td></td>
<td>R, SA</td>
<td>Limestone</td>
<td>Fairly cemented by reddish-brown clayey materials.</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>3</td>
<td>2 – 10</td>
<td>R</td>
<td></td>
<td>Few pebbles almost loose in a clayey soil.</td>
</tr>
<tr>
<td>5</td>
<td>Lower eastern part</td>
<td>2.5</td>
<td>3 – 25</td>
<td>SR, SA</td>
<td>Limestone with gypsum</td>
<td>Pebbles are cemented by clayey and gypsiferous materials.</td>
</tr>
<tr>
<td>6</td>
<td>Upper eastern part</td>
<td>3</td>
<td>1 – 10</td>
<td>SA</td>
<td>Limestone</td>
<td>Top soil cover with loose rock fragments and pebbles.</td>
</tr>
</tbody>
</table>

SR = Sub-rounded, SA = Sub-angular, and R = Rounded

Figure 6: **Left** The apex of Darbendi Bazian alluvial fan, **Right** The sediments at the apex area
3.2. Genesis

As the genesis of Darbendi Bazian alluvial fan is concerned, fans are classified according to the genetic sense by Blair and McPherson (1994) in Ritter et al. (2002) into two types: Type I and II. The classification depends mainly on grain size: their shape and sorting, feeder channel length, drainage basin size, bed rock lithology, and average slope. Following these parameters, the alluvial fan is classified as Type I.
3.3. Mode of Deposition

To delineate the mode of deposition of Darbendi Bazian alluvial fan, the concept of Ritter et al. (2002) is followed besides the available data about the characteristics of the alluvial fan (Table 2). Accordingly, the depositional model of the alluvial fan is constructed (Fig. 10). It could be seen that the deposition starts with Transitional flow and continues in Debris flow, then flows again by Transitional flow, changes to stream flow, and terminates in erosion process, the debris flow being the dominant mode. The last mode of deposition (stream flow) in the alluvial fan is indicated by the supply of the fine materials nowadays, as indicated from the top soil cover (Figs. 6 and 9), where the valleys have no more load-carrying ability to transform boulders, because of decrease in amount of rain water precipitation, and then the role of the erosion; accordingly, almost lost its shape because of cultivation activities and urbanization (Fig. 1). It is worth mentioning that the fan was deposited by Tinal stream, which has changed its direction and flows out of Qara Dagh Mountain through Bassara gorge (Fig. 2).

Figure 9: Darbendi Bazian alluvial fan sediments at Station 6

Figure 10: Conceptual model showing the change in the water/sediments ratio, the sequence of depositional and erosional events and associated flow conditions in Darbendi Bazian alluvial fans (modified after Ritter et al., 2002)
3.4. Abandonment of Darbendi Bazian Alluvial Fan

Alluvial fan is an old and abandoned fan; the indications are: 1) no feeder channel exists in the fan, it is covered by recent sediments (Fig. 11), 2) the fan lost the typical fan shape, 3) at the toe area, active erosion started by active streams (Fig. 11), and 4) the pebbles of the fan at the toe area are already loosening and accumulated as loose pebbles on the slopes of the underlying folded rocks (Fig. 12).

3.5. Age Dating

Absolute dating techniques are not available to the authors, but they believe that the age of Darbendi Bazian alluvial fan is most probably of Late Pleistocene. This assumption is based mainly on the climatic changes during Pleistocene and the existence of the Bai Hassan Formation (Pliocene – Pleistocene) below the sediments of the alluvial fan.

Figure 11: Satellite image of Darbendi Bazian alluvial fan. Note the absence of the feeder channel, the recent valleys (R F) that supply sediments that cover the whole map by soil, and the active streams (A S) at the toe area that started eroding the fan.

Figure 12: Toe area of Darbendi Bazian alluvial fan, note the eroded part of the fan and accumulation of loose gravels on the slopes of the underlying folded rocks.
4. LATERAL GROWTH INDICATIONS

Different authors have studied geomorphological and structural indications that confirm the lateral growth of fold; among them are: Oberlander (1985); Keller and Pinter (2002); Bennett et al. (2005); Ramsey et al. (2008); Mumipour and Najad (2011); Grasemann and Schmalholz (2012); Mousavi and Arian (2015); Whitney and Hengesh (2015); Collignon et al. (2016). In the study area of Darbendi Bazian alluvial fan the following indications were recognized.

4.1. Wind Gap

When a stream abandons crossing a fold owing to natural reason(s), the empty gap that is left is called the Wind Gap (Ramsey et al., 2008). Darbendi Bazian is a typical wind gap developed within the southwestern limb of Qara Dagh anticline (Sissakian and Fouad, 2012 and 2014a and b, and Sissakian et al., 2018). The stream that was crossing the anticline through Darbendi Bazian is called Tinal, which flows nowadays in an opposite direction and parallel to the southwestern limb (anticlinal ridge) of Qara Dagh anticline and flows out of the ridge through a gap called Bassara gorge (Fig. 2). Before changing the flow direction of Tinal stream, it was flowing out of the anticlinal ridge through Darbendi Bazian gorge. The indication for that is developed Darbendi Bazian alluvial fan (Figs. 1, 2, and 11). The presence of a wind gap at a fold is a solid indication that the fold is exhibiting lateral growth (Ramsey et al., 2008) and accordingly witnessing Neotectonic activity (Skilodimou et al., 2014), they revealed the importance of lateral growth and uplifts of folds as indications of active tectonics.

4.2. Abandoned Alluvial Fan

As we have aforementioned and indicated that Darbendi Bazian is an abandoned fan; therefore, this is another indication for a Neotectonic activity and accordingly confirms the lateral growth of Qara Dagh anticline. Many authors have confirmed that one of the indications is the presence of abandoned alluvial fans; among them are: Oberlander (1985); Keller and Pinter (2002); Bennett et al. (2005); Ramsey et al. (2008); Dorn (2009); Grasemann and Schmalholz (2012); Baker et al. (2015); Collignon et al. (2016).

5. DISCUSSION

In a tectonically active area like the Iraqi Kurdistan Region which form the extreme northeastern part of the Arabian Plate and which is in collision with the Iranian Plate, the lateral and vertical growths of the folds is a common fact (Berberian, 1995; Keller and Pinter, 2002; Alavi, 2004; Ramsey et al., 2008; Grasemann and Schmalholz, 2012; Collignon et al., 2016). Accordingly, Qara Dagh anticline is one of those folds that exhibit lateral growth; as indicated by the presence of wind gap that was a water gap and through which a large alluvial fan was deposited by Tinal stream. Owing to the lateral growth of Qara Dagh anticline, the Tinal stream changed its flow direction and no water was flowing in the water gap; accordingly, it was changed to a wind gap. Therefore, the existing Darbendi Bazian alluvial fan was abandoned because no sediments were laid down. However, recently, fine sediments are deposited from small valleys located east and west of Darbendi Bazian gorge (Fig. 11) and accordingly, the abandoned alluvial fan is covered by top soil.

6. CONCLUSION

From the current study, we can conclude that Qara Dagh anticline is exhibiting lateral growth as indicated by the presence of one wind gap, which is present in Darbendi Bazian gorge, and the presence of abandoned alluvial fan, which is present as Darbendi-Bazian-Abandoned alluvial fan. For both cases, we have presented many indications that confirm the presence of a wind gap and an abandoned alluvial fan, including the pebbles that are totally derived from the Pila Spi Formation. The shapes and roundness’s of the pebbles indicate that they are sediments of alluvial fans. The limits of the Darbendi-Bazian-abandoned alluvial fans are hindered below the sediments of recent alluvial fans, which are under development east and west of the abandoned Darbendi Bazian alluvial fan. Besides, the slope sediments which are derived from the slopes of the south western limb of Qara Dagh anticline, which have contributed in hindering the concave fan shape.
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