Investigation on Alamparai Fort by utilization of organic materials for improvement of stability of heritage structure

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Received: 28 May 2021 / Accepted: 24 August 2021 / Published online: 9 September 2021
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Abstract
Heritage structures are valuable monuments that describe the culture and tradition of the country. In today’s world, natural or artificial tragedies alter these historic structures. As a result, restoration was implemented to restore the ancient buildings using modern binding agents to conserve these cultural structures. Rehabilitation can take place only by analyzing the properties of existing structures. The alternative binding additive agent selected can regain the same strength and shape as the heritage structures based on the existing structure properties. Based on these, the restoration of the Alamparai Fort was performed by analyzing the fort materials using mortar strength analysis by core-drilling, double punch test, and small-scale masonry test. The arch properties are also analyzed by performing seismic analysis based on the mortar strength properties. The stability analysis of the organic and existing materials shows that Gur and Haritaki are the best additive agents for restoring the fort. Hence, the fort’s diagonal shear test and seismic modeling were used to analyze the performance of the mortar strength and seismic analysis of these materials. The proposed material strength test results indicate that the Gur and Haritaki are the best additive agents to restore the fort. The fort was restored with these materials; it survived the Nivar cyclone on 26 November 2020.

Keywords Alamparai Fort · Strength analysis · Core-drilling · Diagonal shear · Seismic analysis

Introduction
Most forts in India are castles or fortresses. However, when the Indian government classified India in the seventeenth and nineteenth centuries, they used the term fort that was common in Britain. All fortresses, whether European or Indian, are called fortresses. Since then, this has become common in India. Three main methods were used to construct the Indian castle. The first is the earthen city wall. Usually, they are made of sand, which is dug from the ditches around the fortress. The second layer of rubble is outside, with binding on it, making it stronger. The third type of building is stone and masonry buildings, and the last one is the strongest. Usually, the materials from the demolished fortress are reused to build new fortresses. Although the sudden disaster did not destroy any Indian fortresses, several fortresses were abandoned due to the rulers’ ambitions, and therefore, they deteriorated over time. Few castles have survived since the early Middle Ages and even the fourteenth to fifteenth centuries: most castles built in the tenth to fifteenth centuries have since been remodeled. The castle was used as a residential area until the nineteenth to twentieth centuries, so it was constantly modified.

Alamparai Fort (also known as “Alampara”) was built in the mid-seventeenth century on a historic harbor site. It has seen battles, earthquakes, tsunamis, and the ever-changing tides of imperial power. Alamparai Fort is a historic fortification located in settlement of Alamparai on the Bay of Bengal’s shore. The fort is located about 106 km south of Chennai, Tamil Nadu, India’s ECR. The latitude and longitude are 12.266° N and 80.010° E, respectively. The fort was constructed during the Christian era, under French authority, in 1750 and during the Mughal period. In 1750, the fortress was given to the French for the services provided by the famous French commander Dupleix to Subedar Muzaphar Jung.
When the French were defeated by the British, the fort was occupied and destroyed in 1760 AD. Recently, the structure was destroyed in the 2004 Indian Ocean earthquake. Figure 1 depicts a plan and section view of the Alamparai Fort. The breadth is 177 m, and the length is 218 m. The structure is primarily made up of free-standing brick walls that encircle a large area. The fort bricks were subjected to a stratigraphic investigation, which revealed that they were made between 1700 and 1750 AD. The canal on the west side of Alamparai Fort was built during the British regime in 1878 and exchanged products with rural ships from Marakanam to Chennai until 1967. There is a port on the sea, as well as a commodities exchange pier. Salt and ghee were the main exports from this port. The compressive strength of the Alamparai Fort mortar, on the other hand, has not been explained (Barnaure and Cincu 2020). The walls are unusually shattered and require restoration. The investigation into the current issue is in its early stages.

Fig. 1 Plan and section of Alamparai Fort
There is no standard testing process for ancient buildings. The testing was carried out on the samples or the empirical model of the building. The testing process of existing buildings is broadly classified into three categories. They are destructive, less destructive, and cause minor destruction to the building. The destruction testing causes damage to the building but produces an accurate result on building strength. While in the other two tests, it caused less or no damage to the building. But the results are qualitative, and hence, less destruction type testing is preferred for analyzing the strength of the existing building.

A study on the strength of cultural heritage buildings was conducted (Pelà et al. 2016a, b). Here, a model wall is built by using the same materials as in the cultural heritage building. Then, a cylindrical sample of two sizes, 90 mm and 150 mm, was extracted from the cured wall. Then, the compression and Brazilian tests were performed on the samples. The cultural heritage building strength analysis was performed by conducting a test on different sample sizes. The strength analysis was carried out using core-drilling (Pelà et al. 2016a, b). But in this, instead of the water-cooling system, the dry air-cooling system was used to cool down the core bit during the cylinder extraction process. It reduces the failure of the samples during the test process. The strength of the Cracow building analysis was carried out using the test’s core-drilling process and mathematical modeling based on the material properties (Matysek and Witkowski 2019). Here, the study was carried out only on smaller samples extracted from the building. The sample extraction process causes minor damage to the building. Based on the results, a mathematical model was developed for the analysis of a larger sample size.

The strength analysis of stone masonry was studied (Arède et al. 2019). Here, the properties of stone, infill material, and joints were analyzed by conducting in situ and lab testing. It utilized the core-drilling process to extract a sample from the Vila-Fria bridge. The study results stated that for restoring stone masonry, proper analysis of joint and infill materials required finding the additive agent to replicate the same strength. A less destructive type of test called core-drilling was performed on old brick masonry buildings (Segura et al. 2019). Four samples of two different diameters, 90 mm and 150 mm, were extracted from the building. The first sample was collected from the designed model in a laboratory. The remaining samples were extracted directly from the building and were subjected to compression testing. The results showed that the 90-mm samples exhibit better mechanical strength of the building than other samples.

A study on the mechanical strength of the 100-year-old Australian bridge was carried out by Dorji et al. (2021). Here, forty-five cylindrical samples of different lengths were extracted using the core-drilling process from the bridge. The samples consisted of mortar and various joints of the building. The samples were subjected to a compression test by varying the load and split tensile strength using the Brazilian test. The results showed that the current state of the bridge is suitable for the current loading condition and exhibits good strength.

A study on the mortar strength of current and historical buildings was performed using a penetrometer and a double punch test (Łątka and Matysek 2020). The penetrometer test is similar to the rebound hammer test to measure the hardness of concrete. Then, the surface disturbance zone is estimated before the double punch testing process. The test results show that historical buildings have greater mechanical strength than current building structures. A lime mortar and clay brick wall mechanical strength test were performed using three types of moderate destruction type testing in the laboratory (Pelà et al. 2018). The three testing methods are helix pull-out testing, pin-penetration testing, and the double punch test. Based on the test results of the wall, it was observed that these tests were suitable for analyzing the strength of historic buildings. The modeling and seismic analysis of the Kancheepuram temple were carried out (Ronald et al. 2018). Therefore, in this study, the strength of the existing materials and blocks produced by the combination of Gur and Haritaki were analyzed. The analysis found that the proposed material (Gur and Haritaki) combination has higher strength than existing materials. The fort can be reconstructed from the proposed materials. Since the Alamparai Fort was repaired with the recommended materials, it remained unaffected by Hurricane Nivar.

Materials and methods

The strength of the existing and proposed materials was analyzed based on their quality by conducting various tests. The tests are as follows:

- Analysis of properties of existing materials.
- Strength analysis of existing materials.
- Strength analysis of proposed materials.

Analysis of properties of existing materials

In this, the properties of the Alamparai Fort were studied by conducting characterization of materials, water absorption, and particle size distribution tests. These tests were carried out on the ten samples collected from the building of both bedding and plastering mortar samples. The characterization of the material test indicates that the materials are rich in calcium components by having 85% of calcium oxide. It also contains high traces of other calcium components like Portlandite and aragonite presented in Fig. 8. Based on the statement from Ravi et al. (2018) about the lime plaster analysis of Charminar, this high-rich component is responsible for
the longevity of the fort. The water absorption test indicates that the existing samples increase their weight by 15.04% after 72 h. The results depicted that the bricks absorb more water as time flew and reduces the building strength. The particle size distribution test described that the samples were made of fine aggregate. Retaining the particles allows an increase from 12 to 100% as the sieve size increases from 4.75 to 0.075 mm (Santhanam et al. 2021).

**Strength analysis of existing materials**

In this, the quality and lifetime of the current state of the Alamparai Fort are studied with rebound hammer test, core sample test and water absorption. The requirements and setup procedure for each test are explained in this section.

The primary test for the analysis is the compressive and flexural strength of the material after 28 and 90 days of building bricks from the sample collected from the Alamparai Fort. Another method for measuring compressive strength is the rebound hammer test. The rebound hammer test was carried out as per IS 13311 (IS 13311 (Part 2)—1992) using a rebound hammer. This test depicts the quality of the hardened mortar by applying pressure to the building through a device (Naraynamugam et al. 2019). The device is made up of spring material, so it rebounds to the value based on the hardness of the concrete. The quality of the concrete is weak if it has a low rebound value and vice versa.

A non-destructive method for finding the compressive strength is depicted in Fig. 2a by using the Schmitt hammer. The rebound hammer test was carried out in all four directions (i.e., East, West, North, and South) of the Alamparai Fort. The test values have been calculated at 4 locations (10 readings in each location) as shown in Fig. 2a using a rebound hammer. The aim of this test was to see if there was a link between in situ bricks in a masonry wall and laboratory average compressive strength measurements. The maximum compressive strength for each direction of the wall is 17.45 Mpa, 37.88 Mpa, 33.51 Mpa, and 42.70 Mpa. The compressive strength varied between 11.40 Mpa and 42.70 Mpa. The east-facing wall has minimum strength due to bombasts and is struck by high waves during cyclones and tsunamis. It indicates that the east-facing wall requires restoration to retain the shape of the Alamparai Fort. The strength of the historical materials of the Alamparai Fort was analyzed by conducting Brazilian tests like the core-drilling test and double punch test on the materials collected from it.

**Core-drilling test**

In this, the core-drilling test was carried out in a horizontal direction (i.e., perpendicular to the direction of the wall) using a core bit of 90 mm in diameter. As the drilling progresses, the bit gets hotter. The air cooling with an aspirator is used instead of a water-cooling system to cool down a bit. The water-cooling system leads to water absorption in the building, which degrades the building’s strength. The air-cooling system avoids this degradation. Another advantage of this system is that it utilizes an aspirator, which cleans the dust from the drilling, because the accumulation of dust on the specimen also degrades the evaluation process. Here, the core-drilling extracts four samples from the Alamparai Fort from four directions of the wall. The diameter and height of each block are the same as 90 mm and 200 mm, respectively.

The process of extracting the sample from the Alamparai Fort of size 90 mm in diameter and 200 mm in height is depicted in Fig. 2b, and it is the same for all other samples. Some of the blocks break down during the testing process displayed in Fig. 2d; it is due to the dust accumulation during the drilling process. The final core samples for testing are displayed in Fig. 2c; they are collected by cooling the bit step by step and cleaning the bit frequently using an aspirator. Then, the obtained core samples are subjected to the Young’s modulus test and water absorption test to analyze their strength.

In addition to the compressive strength, the stress-strain behavior, including the post-cracking behavior, was determined. Dividing the applied force by the cross-sectional area and dividing the mean of both longitudinal displacements by the height of the test specimen, respectively, lead to the stress-strain relations plotted in Fig. 3a. Both the compression

![Fig. 2](a) Rebound hammer test, (b) core-drilling at north side wall, (c) different shapes of core samples, (d) failure of sample test
strength and stiffness exhibit a large dispersion, and the ductility behavior is different for each tested specimen. While both the red and the black stress-strain relations indicate large deformation ability, the three other curves show the brittle fracture. All test specimens show almost linear stress-strain behavior up to the compressive strength. However, no pronounced hardening such as in concrete can be observed.

Two further displacement transducers recorded the lateral displacement to obtain information on Poisson’s ratio, which represents the quotient of the mean lateral to the mean longitudinal deformation. In Fig. 3b, Poisson’s ratio is plotted against the compressive strain in the elastic range of deformation from 1 to 2%. For the considered brick specimens, Poisson’s ratio is relatively small, between 0.05 and 0.12. Table 1 presents the material parameters of the core samples.

The core samples taken after performing Young’s modulus test on the core samples were subjected to the water absorption test. The initial weight of the core samples before the water absorption test was 2.796 kg, 2.824 kg, 2.678 kg, and 2.972 kg. The water absorption was carried out by immersing the samples in water for 3 days. At the end of each day, its weight is measured to determine the amount of water absorbed by the brick. Each core sample increased its weight by 9.58%, 9.8%, 9.63%, and 13.05% after 24 h. At the end of 3 days, the total weight of the samples increased by 10.15%, 10.45%, 10.34%, and 16.76%.

Small-scale masonry test

A small-scale masonry test analyzed the strength of the mortar joints. Here, the mortar joint between two bricks is used for testing purposes. The joint was subjected to the uniaxial compression test as in Fig. 4a.

The brick-mortar joint was tested by applying pressure to both sides of the bricks. Three different colors in Fig. 4b indicate the stress-displacement curve caused in the brick-mortar joint due to the uniaxial stress on the three different samples from the Alamparai Fort. Both uniaxial compression tests were conducted on specimens consisting of two bricks of 4-cm edge and a mortar joint with a 10-mm & 20-mm thickness, respectively. The displacement is higher when the pressure applied to the joint increases. Based on the statement from Furtmüller et al. (2012), the cracks in the heritage structure are due to the triaxial pressure developed in the brick. It weakens the joint and reduces its strength. It causes a crack on the outer part of the wall.

Double punch test

The double punch test is an essential method for analyzing the mortar strength of historical buildings by following the DIN 18555-9:1999 standard (Marastoni et al. 2016). Here, the test was carried out by applying a load of 4 KN cells using a compressive machine and two special punching devices to the mortar extracted from the building. It is also a uniaxial strength test, and it causes cracks in the mortar, as in Fig. 4c. The crack occurs due to the triaxial pressure developed during the test process on a smaller mortar area. The mortar specimen height used in the DPT tests was equal to the bed point thickness. As per DIN18555-9 standard, the mortar specimen dimension was approximately 50 mm. The strength (Łątka and Matysek 2020) for producing the crack during the DPT was calculated using Eq. 1.

\[
\sigma = \frac{F_{\text{max}}}{\pi r^2}
\]

where \(F_{\text{max}}\) is the maximum experimental load, and the radius is 10 mm. Based on this, the double punch test was carried out on five samples extracted from four-wall directions (i.e., east, west, north, and south) from the Alamparai Fort. The corresponding mortar thickness and its compression strength are tabulated in Table 2. Figure 4c shows that the sample got cracks when the maximum load was applied.

The cylindrical samples of two diameters, 90 mm and 120 mm, were collected from the Alamparai Fort using a core-drilling process. These samples were subjected to a load test to determine the tensile strength of the material. In this, the load varies from 0 to 35 KN. Then, the displacements in length and width are measured using the horizontal and vertical LVDT. Based on this displacement and the load, the
tensile strength is calculated using the formula [16]. The tensile strength in Table 3 indicates the strength between the mortar and the brick, while in compression strength, the mortar bonding is only analyzed. Due to this, there is a variation in the values of tensile strength.

**Marsh cone test**

The cracks in the walls are cured by injecting the mortar mixture into them, restoring the ancient structures. This mortar mixture should have good fluidity; it also possesses greater strength to renovate the building. The mortar mixture fluid nature was studied using the marsh cone test by following ASTM C939 and EN445 standards (Devi 2020). Based on the XRD analysis, lime is the base mortar in the Alamparai Fort construction. Hence, in this, the lime is mixed with two solutions. One is water; the other is organic water. Organic water is the admixture that improves the strength of the building. A mass of 2.5% organic water has been taken along with Gur and Haritaki and kept 15 days for the fermentation process. After the process of fermentation, the solution is extracted.

Then, Gur and Haritaki, the solutions, are subjected to the marsh cone test by injecting the mixture into the marsh cone as in Fig. 5a upper picture, and it is time to reach the container; its value is tabulated in Table 4. As per the ASTM C939 standard, the proposed organic mixture consumes less time for discharge from the marsh cone of 7.68 s than the 13.02 s for the lime mixture. The minimal discharge time indicates that the proposed organic matter can fix the crack effectively in the walls of the Alamparai Fort. The stability test was conducted by observing zero variation in the final product between the water and organic mixtures per ASTM C940 standard, because zero variation in the mix can exhibit the homogeneity property as it hardens in the future. Figure 5a shows that the proposed organic mixture exhibits homogeneity between both the mixtures. Therefore, the proposed organic solution could restore the Alamparai Fort. Then, the proposed organic matter is subjected to different tests to evaluate its strength.

**Diagonal shear test**

The proposed Gur and Haritaki were mixed in different proportions with lime and sand to form a mortar mixture. By using this mixture, the square block is built up to perform the diagonal shear test. The diagonal shear test was carried out on the square-shaped block by applying the load in a vertical direction from the top side and its force transmitted to the bottom side as in Fig. 5b, and it has two displacement transducers attached in horizontal and vertical directions to measure the variations in length and width of the block. Based on the displacement values from the transducers and the formulas used in Milosevic et al. (2013) to calculate the
shear stress, shear strain, rigidity modulus, and tensile strength, these values are tabulated in Table 5.

Based on these values, the deflection of the building versus load is plotted in Fig. 5c, and it shows that as the load progresses, the deflection of the structure tends to increase, and it may result in a deformed state of the building. All the above strength analysis was performed only on the walls of the Alamparai Fort. The main block arch of the fort is not analyzed. Most historical architecture also carried out analysis only on the walls and blocks of the building. Hence, in this case, the arch analysis was conducted by performing seismic analysis using Ansys software.

The purpose of modal analysis is to analyze the behavior of the building under seismic conditions. During seismic conditions, the building gets excited; it gets damaged when the earthquake frequency exceeds its natural frequency. The results from the strength of the core samples to determine the Poisson ratio, shear strain and stress, and Young’s modulus). The modal analysis of the conical arch was carried out using Ansys software. Then, it is subjected to vibrations of different frequencies as tabulated in Table 6.

The arch gets excited about each frequency, but its shape deformed when it excited two modes, mode 5 & mode 8. During these two modes, 5 and 8, the arch starts to deform towards the right or left direction, as in Fig. 6a–h. The individual responses of the building concerning the time of the vibrations are displayed in Fig. 7a–f. The above responses are the existing material-based arch responses during seismic frequency ranges from 2 to 310 Hz. The peaks in the response curve indicate the natural or cutoff frequency of the arch. The term cutoff frequency indicates the starting frequency of building deformation. Based on the response curve for all conditions like acceleration to stress, the building deforms.

| Sample collection | No of samples (pcs) | Specimen thickness (mm) | Average specimen thickness (mm) | Avgload (KN) | Values (Mpa) | Avgvalue (Mpa) | Standard deviation (values)(Mpa) | Standard deviation (thickness)(Mpa) | COV (values) | COV (Tk) |
|-------------------|--------------------|------------------------|-------------------------------|-------------|--------------|---------------|-------------------------------|-------------------------------|-----------|--------|
| East wall         | 5                  | 13.7                   | 13.52 (17.52)                | 3.68        | 1.79         | 2.62          | 0.66                          | 1.07                          | 0.25      | 0.41   |
|                   |                    | 15.5                   |                               |             | 2.95         |               |                               |                               |           |        |
|                   |                    | 12.5                   |                               |             | 2.92         |               |                               |                               |           |        |
|                   |                    | 13.2                   |                               |             | 1.92         |               |                               |                               |           |        |
|                   |                    | 12.7                   |                               |             | 3.52         |               |                               |                               |           |        |
| West wall         | 5                  | 12.8                   | 14.86 (19.61)                | 3.92        | 2.89         | 3.18          | 0.47                          | 1.66                          | 0.15      | 0.52   |
|                   |                    | 14.2                   |                               |             | 2.65         |               |                               |                               |           |        |
|                   |                    | 16.4                   |                               |             | 2.92         |               |                               |                               |           |        |
|                   |                    | 13.7                   |                               |             | 3.92         |               |                               |                               |           |        |
|                   |                    | 17.2                   |                               |             | 3.52         |               |                               |                               |           |        |
| South wall        | 5                  | 11.6                   | 13.68 (18.43)                | 3.27        | 3.68         | 3.09          | 0.73                          | 2.42                          | 0.24      | 0.78   |
|                   |                    | 12.7                   |                               |             | 3.92         |               |                               |                               |           |        |
|                   |                    | 18.4                   |                               |             | 2.72         |               |                               |                               |           |        |
|                   |                    | 12.5                   |                               |             | 1.86         |               |                               |                               |           |        |
|                   |                    | 13.2                   |                               |             | 3.27         |               |                               |                               |           |        |
| North wall        | 5                  | 13.2                   | 15.35 (19.61)                | 3.78        | 3.72         | 3.87          | 0.65                          | 2.35                          | 0.17      | 0.61   |
|                   |                    | 14.6                   |                               |             | 3.92         |               |                               |                               |           |        |
|                   |                    | 17.7                   |                               |             | 4.72         |               |                               |                               |           |        |
|                   |                    | 12.7                   |                               |             | 2.76         |               |                               |                               |           |        |
|                   |                    | 18.5                   |                               |             | 4.27         |               |                               |                               |           |        |

The specimen total thickness is shown in brackets (with the gypsum caps)

| Table 3 Tensile strength test on core samples |
|---------------------------------------------|
| Sample name | Diameter and height (mm) | Area (mm²) | Tensile strength (N/mm²) |
|-------------|--------------------------|------------|--------------------------|
| ST-1        | 90 & 200                 | 6362       | 0.34                     |
| ST-2        |                         |            | 0.36                     |
| ST-3        | 150 & 200                | 17672      | 0.57                     |
| ST-4        |                         |            | 0.68                     |
after mode 5, because the values get reduced at this point. Therefore, the strength of the arch was also analyzed by this seismic analysis.

The above strength analysis determines that the Alamparai Fort requires a restoration process to restore its historical heritage for longer periods. Based on the stability test results, the Gur and Haritaki were used in a mortar mixture with lime to restore the fort.

Characterization techniques

Acid loss test

The acid dissolution test (Moropoulou et al. 1995) found that the sufficient ratio of lime mortar and sand mixture for the sample is 1:3 (lime:fine aggregate) from Table 7. The wet chemical analysis determines the binder-aggregate ratio (B/Ag). It found that the former part contained calcium, magnesium, Al₂O₃, Fe₂O₃, and soluble silica. Based on the CaO to MgO ratio, the type of binder (calcific/dolomitic) was determined.

The mechanical characteristics of mortars rely upon the binder type and its mix ratio (Gulec and Ersen 1998, Binici and Akcan 2015.). In accommodating lime mortar pores, the binder-aggregate ratio (B/Ag) is a critical parameter and directly affects the dissemination of CO₂ in the lime matrix. In his ten books of architecture, Vitruvius, chapter IV (Rowland and Howe 2001), claimed that lime mortar of 1:3 mix ratio is excellent for higher carbonation. The ancient architects, who were constructed with B/Ag of 1:3, achieved higher strength and toughness (Surendran et al. 2017). The consumption of CO₂ to form CaCO₃ makes it an environmentally friendly building material during its healing and hardening process (Dai et al. 2019).

XRD and XRF analysis of lime mortar

The XRD results mainly depict the carbonation process’ speed in the calcium present in the lime mortar shown in Fig. 8. Under high pressure, orthorhombic crystalline aragonite (fibrous) is formed, and the vaterite with a unique structure is the most unstable polymorph of CaCO₃ (Degloorkar and Pancharathi 2020). The primary compound is calcite, which is found abundantly in both plaster and binder mortar, indicating the utilization of lime in the mortar (Ghadban and Ashhab 2011; Cobirzan and Balog 2014). The carbonation process’ speed is visualized by having high CaCO₃ components like calcite, Portlandite, and aragonite. Therefore, the aggregate of the mortar is not carbonized. The siliceous aggregate, the peaks of calcite and aluminum silicate, may come from the binder. Therefore, the binder may be air lime with CaCO₃ and Al₂O₃ impurities.

In Table 8, the chemical properties of lime mortar samples are analyzed by the XRF process. The hydraulic and cementation index values are measured and are confined to the 0.05 to 0.12 and 0.10 to 0.12 range (Shanmugavel et al. 2020, Ramadosset al. 2019). Hence, the binder is categorized as air lime. The lime mortar sample AAF1 achieved a better cementation index. The brick in the lime mortar is attributed to a low amount of clay minerals. The clay bricks have a high amount of calcite and aluminum oxides (Dizhur et al. 2017). The load-bearing calcium carbonate compound may have resulted in a high percentage of calcium oxide. The presence of silica and aluminum oxides may be beneficial for the pozzolanic action of lime mortar. The sample study found out that air lime mortars were used to build the fort of Alamparai. Therefore, in the proposed, air lime can be used as the mortar mixture base.

Table 4 Marsh cone test

| S. no | Description       | Time taken to discharge (s) |
|-------|-------------------|-----------------------------|
| 1     | Lime + water      | 13.02                       |
| 2     | Lime + organic matter | 7.68                      |
SEM analysis

The SEM test is carried out on the mortar samples to evaluate the hardening process. The calcium carbonate present in the mixture is seen from the SEM analysis, and the voids found in the mix are explained. Figure 9a, b shows the SEM results of the plaster sample with lime mortar mixture. It shows that there is a large calcite formation as well as it has voids in it. This void is responsible for letting water in and forming cracks.

Similarly, Fig. 9c, d shows the results for bedding mortar sample mix, and it also indicates cracks and good calcite formation. The existence of organic admixtures has modified the texture and microstructure of calcite and vaterite. Vaterite rhombohedra crystals (Alonso-Olazabal et al. 2020) are formed due to organic substances (Cizer et al. 2012). Carbohydrates strengthen the loose structures, leading to improved strength and durability. Therefore, both plaster and mortar samples show good calcite formation but cracks in them. Hence, the additive should be chosen with a higher carbonation process and fewer voids to avoid damage and let water into the building.

FTIR interpretation

The FTIR graphs of the various samples are presented in Fig. 10. The FTIR analysis was carried out to determine the mixture’s carbonation process, similar to the XRD analysis. In FTIR, the detailed analysis of components is studied to select the perfect additive agent for the restoration. This analysis is also carried out on the residuals of the acid dissolved test. The characteristic peaks of plaster mortar at 3920 cm$^{-1}$, 3889 cm$^{-1}$, 3805 cm$^{-1}$, and 1630 cm$^{-1}$ indicate proteins (Ramadoss et al. 2019). The peaks at 1815 cm$^{-1}$, 1445 cm$^{-1}$, 1795 cm$^{-1}$, 1636 cm$^{-1}$, 879 cm$^{-1}$, and 872 cm$^{-1}$ indicate calcites (Cizer et al. 2012), 1045 cm$^{-1}$, 1114 cm$^{-1}$ indicate carbohydrates (Maravelaki-Kalaitzaki et al. 2005), 618 cm$^{-1}$, 599 cm$^{-1}$ indicate aragonite, and 784 cm$^{-1}$ indicates O–C–O in-plane bending. From the peaks, it is observed that the mortar-based samples have higher carbohydrates as compared to plaster. Due to this, the formation of calcite is higher in plaster as compared to the mortar-based samples. Therefore, as shown by XRD, organic matter such as carbohydrates and proteins and clay impurities such as silica, alumina, and ferrous oxide can be verified in the FTIR results. The broad peak at 3730 cm$^{-1}$ and the hydroxide ion stretching showed isopropanol, ethanol, and CaO were not found in the XRD results.

TGA DTA analysis

TGA-DTA analysis also followed the findings acquired from XRD, SEM, EDS, and FT-IR. In Fig. 11, a dramatic change in weight was 27% between 600 °C and 800 °C, primarily because of the calcite de-carbonation. The findings of the TG study are therefore well in line with the SEM and XRD outcomes. A heavy peak at 470 °C in the adjusted sample shows aragonite available, while no such peak was found, as shown in Fig. 11 (Bakolas et al. 1998). A small exothermic peak for F-2 at 515 °C demonstrates vaterite presence (Moropoulou et al. 2000).

The calcium hydroxide dehydration and DTA curve presence of aragonite and vaterite were compatible with the XRD analysis results. In the sample of F-2, the low and short peak from 700 to 900 °C, the mild endothermic peak at 680 °C from

| Table 5 Material properties of diagonal shear test |
|--------------------------------------------------|
| Samples | Density (ρ) kg/m$^3$ | Young’s modulus (E) N/mm$^2$ | Poisson ratio (μ) | Shear modulus N/mm$^2$ (G) | Shear wave velocity Vs (m/s) |
|---------|---------------------|-------------------------------|-------------------|-----------------------------|-----------------------------|
| I       | 1812                | 554                           | 0.17              | 237                         | 361                         |
| II      | 1811                | 595                           | 0.17              | 254                         | 375                         |
| III     | 1792                | 527                           | 0.17              | 225                         | 355                         |
| I       | 1812                | 554                           | 0.17              | 237                         | 361                         |

| Table 6 Seismic analysis of arch and Fort |
|------------------------------------------|
| Mode | Frequency (Hz) |
| Arch | Fort          |
| 1    | 2.7783     | 0.91447     |
| 2    | 4.6342     | 1.6496      |
| 3    | 6.9002     | 2.0362      |
| 4    | 127.05     | 2.7328      |
| 5    | 135.88     | 2.8298      |
| 6    | 186.49     | 3.7596      |
| 7    | 214.33     | 3.865       |
| 8    | 218.94     | 4.386       |
| 9    | 289.7      | 4.4231      |
| 10   | 310.14     | 4.9585      |
600 to 800 °C are the CO₂ escape during structural disintegration calcite breakdown in Fig. 11 (Bakolas et al. 1998). Organic substances have been confirmed by FTIR analysis and organic tests and clarified by the polymorphs of CaCO₃ formation. Based on the CO₂ weight loss, the amount of calcium carbonate is determined. F-2 (33%) reported a high level of precipitated calcium carbonate in the lime mortar samples, followed by F-1 (27%) and F-2 (19%).

**Fig. 6** Response spectrum analysis of conical arch. (a) Mode 5 (135.88 Hz), (b) Mode 7 (214.33 Hz), (c) Mode 9 (289.7 Hz), (d) total deformation, (e) normal elastic strain, (f) equivalent stress, (g) shear elastic strain, (h) shear stress

### Strength analysis of proposed materials

### Chemical characteristics of lime

The chemical composition of lime-like calcium oxide, magnesium oxide, iron oxide, silica, alumina and their importance on the behavior of lime are dissected to find out the lime class as per IS 6932 (IS 6932 (Part 1)-1973). The chemical
compounds present in the air lime are CaO of 80.26%, MgO of 0.001%, SiO$_2$ of 4.648%, Al$_2$O$_3$ of 1.242%, Fe$_2$O$_3$ of 1.289%, and loss on ignition of 12.56%.

Based on XRF results, the lime could be categorized as high calcium lime with a CaO content of 80.26%. As per IS: 712 (IS 712 - 1984), we could use lime for structural purposes like bedding, mortar, and plaster. The lime’s elemental composition is shown in Table 9 and shows that the lime’s oxygen content is high. Because of this higher oxygen relative to the calcites, Portlandite formation would be more significant. It is observed that the Portlandite is higher as compared to the calcium carbonate components like calcium oxide and calcite and brucite in Table 9. Calcite is stable and has a hexagonal structure at an average temperature. Aragonite is

Table 7 Results on acid loss test

| Sample ID | Initial weight (g) | Acid loss (g) | Weight after acid loss (g) | Weight of sand retained (g) | Weight of binder (g) | B/A ratio  |
|-----------|--------------------|---------------|---------------------------|----------------------------|---------------------|-----------|
| F-1       | 100                | 7.2           | 92.8                      | 68.6                       | 24.2                | 1:2.83    |
| F-2       | 100                | 7.9           | 92.1                      | 69.4                       | 22.7                | 1:3.05    |
| F-3       | 100                | 7.4           | 92.6                      | 71.2                       | 21.4                | 1:3.33    |
| F-4       | 100                | 7.3           | 92.7                      | 69.9                       | 22.8                | 1:3.03    |
| F-5       | 100                | 6.9           | 93.1                      | 68.42                      | 24.68               | 1:2.77    |
formed under high pressure, while vaterite stone is a relatively unstable polymorph of CaCO₃ (Fiori et al. 2009).

Further, the CaCO₃ polymorphs occur because of a self-healing process with the presence of Mg. Due to low calcium formation, the carbonation is less in ordinary lime mortar. Hence, an additive agent is required to improve the carbonation process.

The experimental analysis of sample materials from the Alamparai Fort observed that the fort was made up of calcium-rich and fine-sized elements. According to IS 712 (IS 712-1984), air lime is used as the basis for mortar mixture in existing material. Hence, in the reconstruction of materials, air lime is used as the base mortar. The XRD and XRF analysis of materials indicate that materials composed of a calcium-rich element exhibit greater strength. Hence, Gur and Haritaki were used as binding additive agents in the mortar mixture for restoring the Alamparai Fort. The tannic acid present in Haritaki exhibits greater strength due to its stronger bond between the elements. Hence, the proposed binder agent can restore the fort effectively as the same as the existing materials. The lime and sand are mixed in a ratio of 1:3 as per IS standards (IS 712-1984). The Gur and Haritaki are mixed in an equal ratio to the base mortar. The Gur and Haritaki mass ratio varied from 2.5 to 12.5% to analyze its strength and find the right proportion for restoration.

The proposed mortar mixture was molded into a brick of 50 mm × 50 mm × 50 mm in size. Then, the molded brick is subjected to compressive and flexural strength by applying a low pressure. Both compressive and flexural strength were observed for two time periods. One is 28 days; the other is 90 days. The compressive strength of different samples for 28 days was 1.65 N/mm², 1.72 N/mm², 1.92 N/mm², 2.15 N/mm², and 2.94 N/mm². At the end of 90 days, its strength improved by 1.84 N/mm², 2.48 N/mm², 2.44 N/mm², 2.56 N/mm², and 3.96 N/mm². The hardened mortar increases its compressive strength by 1.5% from its initial value as time progresses. Similarly, the flexural strength of the proposed mortar samples was also calculated. It is conducted by applying low pressure to the bricks of 160 mm × 40 mm × 40 mm. The flexural strength also improved its strength at the end of 90 days to 0.86 Mpa, 0.86 Mpa, 0.94 Mpa, 0.96 Mpa, and 1.3 Mpa for different mortar mixture samples.

Comparison between proposed and existing mortar sample

The brick sample obtained from the fort is of size 215 mm × 103 mm × 35 mm, and the same size of simulation brick is tested for estimation of the water absorption rate. Nearly four brick samples were used for testing (Ronald et al. 2018). From the brick water absorption results, it shows that the old brick absorption rate was 10.65%, 10.70%, 8.29%, 10.49% at 24 hours and 12.57%, 14.63%, 12.95%, 14.90% at 72 h. For the simulated bricks, the water absorption rate is 9.02%, 11.28%, 7.3%, 7.07% at 24 h and 17.16%, 17.26%, 14.47%, 7.07% at 72 h. The water absorption rate of the simulated brick is almost 13% less than the old brick. The presence of protein content in the Jaggery-Kadukkai provides an excellent water repellent coating on the brick. Overall, the proposed Jaggery-Kadukkai based mortar is excellent in terms of strength and water resistance. Therefore, the restoration using the proposed mortar provides longer durability of the conditions with great strength.

The proposed materials were subjected to a water absorption test; the results indicate that they increased their weight by 7.07% only after 72 h. Therefore, the proposed Gur and Haritaki based mortar can increase the lifetime of the fort by absorbing less water.

Table 8 XRF results of samples

| Samples | CaO   | Al₂O₃ | MgO   | Fe₂O₃ | SiO₂ | So₃   | K₂O   | H₂O   | CI    | LOI  |
|---------|-------|-------|-------|-------|------|-------|-------|-------|-------|------|
| F-1     | 85.23 | 0.82  | 1.28  | 1.74  | 2.43 | 0.96  | 0.24  | 0.13  | 0.19  | 25.28|
| F-2     | 82.43 | 3.97  | 0.86  | 1.96  | 0.46 | 1.27  | 0.36  | 0.12  | 0.13  | 19.78|
| F-3     | 84.59 | 1.16  | 0.7   | 1.68  | 0.3  | 0.17  | 0.24  | 0.11  | 0.04  | 16.72|
Modeling and analysis of proposed organic materials

In this, the results of both the existing and proposed mortar samples are analyzed to identify the quality of the material.

Conical vault arch testing

The Alamparai Fort consists of arches that could not be accessed by using the core-drilling process; it causes damage to the building during the block extraction process. Hence, most of the historical analysis does not perform strength calculations on the arches. Therefore, the arch test has been done in this paper by constructing the arch as in the fort using the proposed binding agent. The measurements for the arch construction were taken from the fort, as depicted in Fig. 12.

Based on the arch measurements from the fort, the front view of the arch shows that it is 40 cm in total height, 21 cm from the inner arch. The radius of the inner arch from its center is 39 cm, 60 cm for the outer arch depicted in Fig. 12a. Similarly, the inner and outer arch width was measured at 21 cm from the back view. The total height is 60 cm, and the radius of the outer arch is 75 cm from the arch center. Using front and back view arch measurements, the arch was built up using three different proportions of organic matter-based mortar mixtures as in Fig. 12b, then the sand load test was carried out on the arch for the strength analysis.

The above conical arch was subjected to a sand load test to analyze its strength under heavy loads experimentally. Similar measurements were used for the seismic analysis of the arch using Ansys software.

Experimental analysis of sand load test on the arch

Here, the arch was built using a Gur and Haritaki mortar mixture; it was cured for ninety days to gain its maximum compressive strength. Then, the conical valley arch is subjected to the load test by applying the sandbag on the top of the arch as in Fig. 12c. Here, the load varies from 0 to 20 KN. During this process, the deformation of the arch was measured using five transducers to measure the displacements in the horizontal left, right, and center and along the left and right side of the arch quarters.

Based on the displacement measurements from the transducers, the relation between the load and displacement is realized in the graphical view in Fig. 13a–c for three different mortar proportions.

The results show that mortar mixture 3 has higher strength by having minimum displacement. Whereas in other mortar compositions, it exhibits a 3-mm displacement for the same load, in mortar mixture 3, its overall displacement is below 3 mm. Experimental analysis of load tests on the arch indicates that the proposed organic Gur and Haritaki are suitable for restoring the Alamparai Fort.
Modeling and seismic analysis of Alamparai Fort using Ansys software

The modeling and seismic analysis of the valley conical arch of the seventeenth century Alamparai Fort in Tamilnadu, India, are discussed in this section. Time history and response spectrum are the two basic methods commonly used for seismic analysis. Time-history analysis is used to determine the dynamic response under the action of any general time-dependent loads. To determine the time-varying displacements, acceleration, equivalent elastic strain, equivalent stress, normal elastic strain, and normal stress. Response spectrum analysis method is used to determine the modal analysis and the behavior of the building under seismic conditions using ANSYS software. It was also used to determine the total deformation, normal elastic strain, equivalent stress, shear elastic strain, and shear stress. During seismic conditions, the building gets damaged when the earthquake frequency equals its natural frequency, and it is subjected to vibrations of different frequencies, as tabulated in Table 6.

During these two modes, 7 and 10, the conical arch deforms towards the south or west wall, as in Fig. 14. The individual responses of the building concerning the time of the vibrations are displayed in Fig. 15a, h. The above responses are the existing material-based arch responses during seismic frequency ranges from 0.9 to 4.95 Hz. The peaks in the response curve indicate the natural or cutoff frequency of the arch. The term cutoff frequency indicates the starting frequency of building deformation. Based on the response curve for conditions like acceleration to stress, the building gets deformed after mode 2 because the values are reduced. Therefore, the strength of the arch was also analyzed by this seismic analysis. In each wall of the fort, there are two full conical arches and two half-conical arches. The fort entrance was located on the north side of the wall; its width is 176.40 m. The north and south sidewall height is 7.60 m from the ground to the arch starting point; the east and west sidewall height is 7.0 m. The total wall width is split between the arches and their centers. The arch gets excited about each frequency, but its shape changes when it gets excited about mode 2.

Discussion

It is found that Alamparai Fort was constructed using a B/Ag ratio of 1:3 in which calcium is observed to be more than 60% as per to IS 712-1984; it is called air lime. The XRD SEM determination validates the mechanical properties that settle the calcite presence along with aragonite and vaterite. The chemical composition of original and repair mortar samples confirms CaO, MgO, SiO₂, Al₂O₃, Fe₂O₃. The results indicate that the strength of the simulation mortar could be similar to the original mortars. Based on the strength and seismic analysis of the proposed and existing materials, the proposed Gur and Haritaki materials are suitable for restoring the fort. It exhibits high compressive strength after 90 days and less displacement in sand-load tests and seismic analysis tests.

| Minerals | Calcium oxide (CaO) | Portlandite (P) | Calcite (C) | Brucite (B) |
|----------|---------------------|----------------|-------------|-------------|
| Intensity| ++                  | +++            | ++          | ++          |

+++ high intense peaks; ++ moderate intense peaks
Characterization of the ancient mortar samples found that the binder to aggregate ratio, chemical composition and mineral composition, organic analysis of bedding and plastering mortar. The characterization results indicate that the strength of the simulation mortar could be similar to the original mortars. Simulated bricks prepared for ancient bricks were based on the weight, dimensions, water absorption, and compressive strength. For example, the brick’s attained size is 215 mm × 103 mm × 35 mm from the fort, and a similar size was used as a model process and tested to evaluate the rate of water absorption. The brick characterization will be useful for the preparation of compatible old bricks and simulated bricks.

![Image](image1.png)

**Fig. 12** Arch from the fort. (a) Existing conical valley arch, (b) simulated conical valley arch, (c) plate load test on arch.

The ancient mortar and bricks were characterized and simulated in the laboratory for this model to be created. Hence, this model, which was developed in the laboratory, signifies the properties of the ancient fort. Therefore, the models made for the replicated conical valley arch are similar to the existing Alamparai Fort. Hence, the proposed model will suit the restoration of the Alamparai Fort. The model was tested on valley conical arch (Fig. 7a) experimentally and analytically (Fig. 6). Valley conical arch experimentally was tested in the laboratory using the existing size of arch, bricks, and binder to aggregate ratio (1:3). While testing, the material properties and load-carrying capacity (Fig. 13) were identified. Using the obtained results, the inputs are given manually in the software and checked analytically. Similarly, for Alamparai Fort (Fig.

![Image](image2.png)

**Fig. 13** Sand bag-load test results on arch I, II, III.

![Graphs](graphs1.png)
from the collected core samples, material properties (Table 1) were identified, and the inputs are applied manually in the software and simulated analytically (Fig. 14).

In general, it is difficult to characterize the mechanical properties of existing mortar in historic buildings by minimizing the damage caused during inspections. In any case, the samples taken from the building should be small enough to reduce esthetic interference, retain the original materials, and avoid the risks and difficulties associated with changing structural members. A small sample can be taken based on the value of the structure and then taken to the laboratory to obtain a direct estimate of the material’s properties.

**Fig. 14** Response spectrum analysis of fort. (a) Mode 2 (1.65 Hz), (b) mode 7 (3.87 Hz), (c) mode 10 (4.96 Hz), (d) total deformation, (e) normal elastic strain, (f) equivalent stress, (g) shear elastic strain, (h) shear stress
In this paper, the response spectrum method and time history analysis method are used to carry out seismic analysis on the Alamparai Fort and arch in Tamil Nadu, India. The research carried out helps to better understand the structure’s behavior and the most susceptible elements of the structure in any seismic event. The uncertainty of material properties and geometric details has been resolved through comprehensive parameter studies. It is worth noting that although structural modeling is greatly simplified, different structural analysis methods can still make similar inferences about the seismic response of fortresses and arches. Some important assumptions from current research can be listed as follows:

- Modal analysis shows that fortresses and arches are the most vulnerable parts of the structure. The aggravated response under seismic excitation is due to its low fundamental frequency. According to the modal analysis graph, the east side arch of the fort was damaged at mode 10 (4.96 Hz). While the arch built using the proposed mortar can tolerate a frequency of up to 289.7 Hz. As a result, the proposed mortar mixture is the optimum restoration alternative.
- Lime mortar is used extensively in the fort. Although the strength is lower, the deformability is higher than other adhesive materials. Therefore, the structure can be expected to have more energy dissipation capacity, which is beneficial to dynamic loads.
- The destruction of the structure evolved from the destruction of the material, and due to its advantageous configuration (pyramid shape), instability should not be a
problem. The natural frequency (0.9–4.9 Hz) is completely separated from the fundamental frequency of the soil (2.8–311 Hz), indicating that there is no possibility of resonance. The acceleration is given based on as per IS 1893: part 1 (IS 1893 (part 1): 2002).

- The mortar joints in the older bricks exhibit greater strength for a 20 KN load. Therefore, the choice of binding agent should replicate this strength. The major conical arch analysis was carried out in this paper by using the strength results from the core-drilling process. The seismic analysis of the arch indicates the building strength by showing smaller displacements.
- Conduct structural analysis of historical buildings to better understand structural behavior and/or obtain residual capacity during structural evaluation and develop strengthening strategies when necessary.

**Conclusion**

The characterization techniques of ancient mortar sample 300-year-old Alamparai Fort was constructed with a binder to the aggregate ratio of 1:2.5–1:3.2, which indicates the best proportion for better strength. The addition of organics to lime mortars increased the characteristics of the mortars significantly. Analytical techniques like XRD, FESEM, FTIR, and TGA were chosen. In XRD, the identified peaks are confirmed with FESEM, FTIR, DTA analysis. Because of the results obtained, the characterization studies were very similar for the restoration mortars studied. Heritage structure restoration can take place only by analyzing the properties of existing structures. The alternative binding additive agent selected can regain the same strength and shape as the heritage structures based on the existing structure properties. Based on these, the restoration of the Alamparai Fort was performed by analyzing the fort materials using mortar strength analysis by core-drilling, double punch test, and small-scale masonry test. In this, the arch properties are also analyzed by performing seismic analysis based on the mortar strength properties. The core-drilling test indicates that the east wall faces greater damage than the other walls by having lower compressive strength.

Based on these, the stability analysis of the organic and existing materials shows that Gur and Haritaki are the best agents for restoring the fort. Hence, the mortar strength and seismic analysis of these materials were performed using a fort’s diagonal shear test and seismic modeling. The proposed material strength tests results indicate that the Gur and Haritaki are the best agents to restore the fort. The proposed material exhibits greater strength after 90 days of cured blocks and produces less displacement of about 1.2 mm for 20 KN loads during sand-load tests and seismic analysis. The materials absorb less water than the existing materials, so they help to increase the building’s longevity. The fort was restored with these materials; it survived the Nivar cyclone that crossed on 26 November 2020.

Therefore, the simulation mortar is a better match with the ancient mortars, which comprise all the elements of the original mortar. The composition of mineralogical characteristics is similar. The strengthening and seismic analysis were determined that the Alamparai Fort requires a restoration process to restore its historical heritage for more extended periods. Based on the strengthening test results, the Gur and Haritaki were used in a mortar mixture with lime to restore the fort. This research concludes that the outcomes of the simulated materials obtained are sufficient to restore the Alamparai Fort.

**Author contribution** KS—conceptualization, methodology, writing, original draft preparation. RR—reviewing, results and discussion.

**Data Availability** All data generated or analyzed during this study are included in this published article.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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