

Smart Structures – Economic Feasibility Study

Team Members:

Louise Colly, Carina Lampl, Ties Marissen, Nadine Worgull

Supervisors:

Pau Martí (UPC – EPSEVG), Félix Ruiz Gorrindo (Neàpolis)

Abstract - In recent years, the Civil Engineering world has seen a change in how to preserve and monitor structures. Thanks to Smart Structure systems, which capture data on pathologies by use of different sensors, deformations in structures can be noticed and anticipated. Different research works are being undertaken on buildings by a variety of institutions such as Neàpolis in Vilanova i la Geltrú.

The aim of this project is to carry out a cost analysis for the implementation of Smart Structures in existing and planned buildings by creating a formula. This study attempts to decide if the Smart Structure systems are feasible in the long term. In order to achieve this, research and knowledge gathering about the cost of sensors and about civil engineering has been necessary.

Thanks to this extensive research and close collaboration with our supervisors and Neàpolis, a formula to apply to the Parroquia Arciprestal Sant Antoni Abat and the Neàpolis building has been created.

Our team comprises four students from different countries and through this project we attempt to prove that despite an initial lack of knowledge about civil engineering, teamwork and project management have enabled us to overcome several difficulties and will enable us to achieve all the objectives within the time frame.

Keywords - Cost Analysis, Formula, Neàpolis, Sant Antoni Church, Savings, Smart Structures

I. INTRODUCTION

As participators of European Project Semester at the Universitat Politècnica de Catalunya a research for a company had to be done. The research that has been done is a feasibility study on Smart Structure systems in buildings. This has been an assignment by Neàpolis an innovation agency that started in 2007 in Vilanova i la Geltrú. As part of the city council of Vilanova i la Geltrú, Neàpolis provides start-up companies with a place to work from and gives advice in the way of doing business. The research has been done in order to give Neàpolis an indication whether Smart Structures are feasible to put into buildings by lowering maintenance cost and improving the life span of buildings. There is not a known study that is similar to this one, in our knowledge this is the first feasibility study on Smart Structures has been performed. The research is of importance to the company, because of their studies on Smart Structures in general they want to have an economical reinsurance of their studies.

II. PATHOLOGIES

There are different kinds of pathologies the developed Smart Structure System has to be able to measure. The most founded damages in buildings are deformation, cracks, humidity and corrosion. This is also what has been found in the Sant Antoni Church and in small parts in the Neàpolis building, therefore the research focuses on these pathologies.

III. SENSORS

Because of the different pathologies, different sensors need to be used. The Fiber Optic sensor is able to detect deformations, humidity and cracks. For this project the best solution is to use multiplex sensors. The measurement in multiplexed sensors is defined by a certain number of fixed, discrete points along a

single Fiber Optic wire. By using this more sensors can be added one single wire. The most common example for multiplexed is Fiber Bragg Gratings. Fiber Bragg Gratings are gratings (*small mirror*) in a Fiber Optic wire to transform short parts of the wire into a Fiber Optic sensor to detect the local environment around the Fiber.

For the detection is white light sent through the wire and the gratings are arranged to reflect particular wavelengths back and transmit all others along the Fiber. The measured quantity such as strain or pressure can then be determined from the wavelength reflected from each grating. The following figure demonstrates this phenomenon.

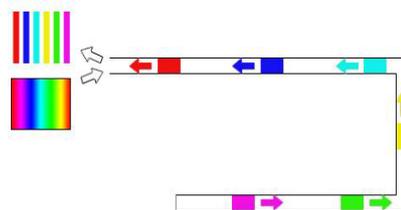


Fig. 1: Fiber Bragg Grating

In this project it is necessary to combine different wires to one system, this can be done with multichannel measurement devices. To measure corrosion a different sensor has to be used.

The Acoustic Emission sensors measures corrosion by the sending of acoustic waves in the structure and receiving back the wave. The sensor measures the acoustic waves of the vibrations, caused by changes in the structure. waves spread from the source in the whole structure. An acoustic noise sensor measures the high frequency waves, in a range from 10kHz up to several MHz and converts them into an electrical signal. The signal will be digitized and analysed by special software.

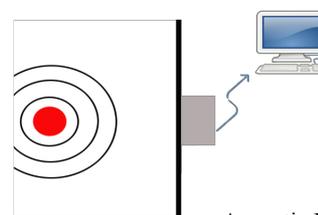


Fig. 2:

Acoustic Emission Sensor

IV. METHODOLOGY

The research focuses on two buildings that both represent a different type of construction. The buildings have been chosen because of these differences, the first building is the Neàpolis (2007) building and the second building is the Sant Antoni church (1693) both located in Vilanova i la Geltrú. To compare these two constructions, add to the wide approach the research takes, including old and new

buildings. This leads to a more general outcome of results for the cost analysis.

To create more savings, for each of the buildings three different intensity concepts of Smart Structure systems have been thought off, these are low, medium and high intensity. The intensities can be different for each building, and even be different in different floors of the building.

V. STRUCTURE SANT ANTONI CHURCH

The Sant Antoni church (1693) has three naves with chapels. The roofs are vault to the main nave until the side edges. There are two facades, one in the Placa de Sant Antoni and the other on the Placa de les Neus. The facade of the Placa de Sant Antoni has 4 large columns compound of decorations on the top with entablature and triangular pediment.

The Sant Antoni Church is an old stone building, so it is advantageous to combine the Fiber Optics with Acoustic Emission sensors. Because the acoustic system permits to deliver data between the stones, it has a high sensitivity. Therefore it is perfect for buildings that are made of stones.

VI. IMPLEMENTATION SANT ANTONI CHURCH

The placement of the sensors has been figured out with the help of the PhD civil and building engineer Félix Ruiz Gorrindo. Also the lecture of the civil engineer Miriam Sorriano has given us a great insight of the placement of the sensors. It has been also of great help the drawings of the church made in the School of Building Engineering of Barcelona (García, I. and Alegret, J., 2010)

As we explained in the section of methodology, we propose three different levels of intensity of implementation of sensors. The low intensity concept is the one that is considered as the basic way of measuring the vital parts of the building. For the low intention there are Optical Fibers and Acoustic Emission sensors. Together they can measure all different pathologies that we defined as necessary to measure in section II.

In Fig. 3, the map of Sant Antoni Church is being displayed with the proposed low intensity level of a Smart Structure system. The sensors will be attached to the columns and the arcs in the outer rows. The green line is demonstrating the optical Fiber wire, the black dots are the FBG-sensors and the green squares are the AE-sensors.

The wires and sensors will be placed, where possible, between the arcs and the roof. Therefore the visual aspects of the building are not damaged. The church has different forms of humidity problems and the main problem is due to capillarity humidity. Because the humidity comes from the ground, 4 sensors are placed in the bottom of the inside of the outer walls, to reduce visual damage to the building. In total the Sant Antoni church will have 16 FBG-sensors and 5 AE-sensors with 176,6 meters of Fiber Optical Cables.

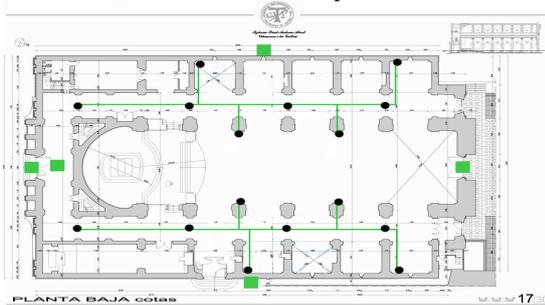


Fig. 3: Low Intensity Concept Sant Antoni Church

In Fig. 4 you can see the proposed medium intensity concept for the Sant Antoni church. This concept is based on the low intensity concept and sensors will be added to the layout. The FBG-sensors that are added will be in the bowls of the chapels in the side of the building. The stress on these bowls is measured for cracks, humidity and deformation. This will add 8 more sensors to the low intensity proposal. There are no additional capillarity humidity points added, because of the ground moisture is the same over the entire ground floor.

For the measurement of corrosion there will be 2 additional sensors on the sides of the long walls. This is going to give a more detailed placement of corrosion. The total system will have 24 FBG-sensors and 7 AE-sensors with total of 293,5 meters of Fiber Optic cable.

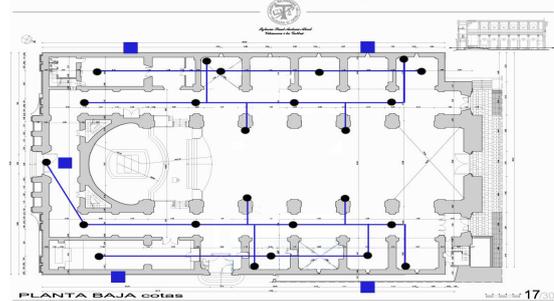


Fig. 4: Medium Intensity Concept Sant Antoni Church

The high intensity concept covers all the pathologies in the different segments of the church. The change of catching pathologies in the early stages will be the highest with this system. In Fig. 5 the high intensity system is displayed. The sensors are added to the grid of the previous proposals. In the centreline of the building we added another 4 sensors in order to measure the bowls and the arcs of the main hall of the church. The visual effect of pathologies is the biggest in this part of the building, however the source mostly lay in other parts of the building. For the corrosion another 5 Acoustic Emission sensors are added to the system. This leads to 3 sensors on each of the long sidewalls and 2 sensors on the front and back facades. Also in this option there are additional Acoustic Emission sensors chosen to place in the ferro concrete. The total system will have 29 FBG-sensors, 11 AE-sensors and 337,5 meters of Fiber Optic cable.

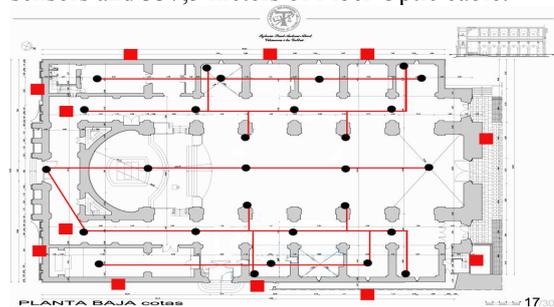


Fig. 5: High Intensity Concept Sant Antoni Church

VII. RECOMMENDATION SANT ANTONI CHURCH

A concept is chosen for the Sant Antoni church by considering the circumstances that influence the church such as; environment, building use and way of construction. For the Sant Antoni church the best solution concerning the Fiber Optics is the medium intensity

concept. This means that the structure will have 24 FBG-sensors to detect cracks, humidity and deformations. The system also includes 12 Acoustic Emission sensors from the high intensity concept. These will detect the corrosion on the outside of the building and the state of the ferro concrete in the main-facade. The building has different pathologies, such as cracks, humidity's and corrosion. We can qualify the general state of deterioration of the building as intermediate. To illustrate this concept, if we take as a reference the scale of gravity of damages in buildings developed in (Ruiz, 2014), the grade of gravity (G) for the whole building should be $G = 5$ (in a scale from $G = 0$ (perfect state) to $G = 10$ (extreme gravity)). Most pathology is already seen by eye, therefore it is not useful to install the high intensity concept. However the San Antonio Church is a historical building and there is a great interest in the preservation of the building, on this account the medium intensity was chosen. This will be more useful because it saves costs but is still giving enough data. The major pathologies are visible so the system only has to give information about the expansion of these damages. The climate of the region has a high influence on the corrosion of the building. The building contains some case of corrosion. This is mainly due to the wind in the coastal climate. Therefore it is a good option to choose the high intensity level for the AE-sensors. The system will be made up of 24 FBG-sensors, 12 AE-sensors and 293,5 meters of Fiber Optic cable.

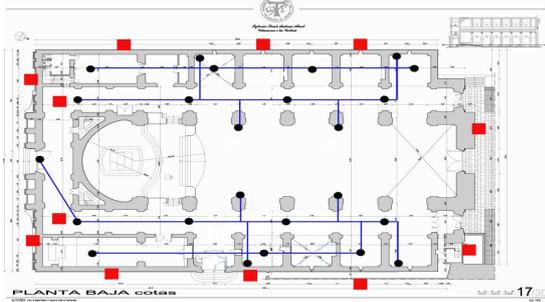


Fig. 6: Recommendation Sant Antoni Church

VIII. STRUCTURE NEÀPOLIS BUILDING

The Building of Neàpolis is around eight years old and has a healthy structure. It consists of five floors. The basement floor, the ground floor, the first, the second and the third floor. The third floor has another structure than the other floors. This floor is made of steel and glass. The main part of the building is made of ferro concrete. The bearing units in the building are the 60 columns, who bear the complete building, except the third floor. The bearing unit of this floor is one great steel beam in the ceiling of the construction. Although there is some slight pathology, such as humidity. In general the structure of the building is healthy. If we take as a reference the scale of gravity of damages in buildings developed in (Ruiz, 2014), the grade of gravity (G) for the whole building in this case should be $G = 1$ (in a scale from $G = 0$ (perfect state) to $G = 10$ (extreme gravity)).

IX. IMPLEMENTATION NEÀPOLIS BUILDING

Every building and each floor has special needs. Therefore for implement the sensors in Building such as the Neàpolis Building, three different Intensity concepts were developed. The first concept is the Low Intensity (Fig. 7) and is develop for floors with a low emergence of stress. It contains three Fiber Optic wires in the ceiling. In the first, the fifth and the ninth row of columns, to detect changes in different parts of

the floor. As it was said in section VIII Structure Neàpolis Building, the columns are the bearing units in the building and it us useful to measure deformation in the ceiling between the columns. This is the part with the most emergence of bending in the ceiling. For this concept there are 14 FBG-sensors required. Sensors will be placed in the middle of the columns in the beginning, the middle and the end of the floor. There are two detected columns in the first row of Sensors, two Sensors in the fifth row and two Sensors in the tenth row. The distances of the columns to the middle and the outer walls are nearly the same. The location of the chosen columns is comparable to nearly all other columns. In total there are 20 Sensors and a length of 70 meters of Fiber Optics cable.



Fig. 7: Low Intensity Concept Neàpolis Building

In the Medium Intensity (Fig. 8) concept, more sensors are used. Starting from the first row of columns, in every second row sensors are installed, also a vertical wire is added to the system. This arrangement enables a greater area of monitoring and some sensors are placed near to the outer walls on the left and the right side. With the medium intensity concept it is possible to measure changes also on the smaller outer walls. The concept also includes the detection of compression in the columns. Chosen are the same columns with the same way of installation as in the low intensity concept described. The total medium intensity concept consist of 40 FBG-sensors and 103,8 meters of Fiber Optic cable.



Fig. 8: Medium Intensity Concept Neàpolis Building

The high intensity (Fig. 9) concept is developed for floors with a great emergence of stress. In horizontal direction is the same arrangement used as in the medium intensity concept. The difference is that two wires with sensors are used in vertical direction, instead of one. The first wire is implemented in the first row of columns and the second wire in the third row. With this arrangement, the parts of the grid are smaller. This enables to measure a greater area of the structure. For the detection of compression is the same concept used as in the low and medium intensity.

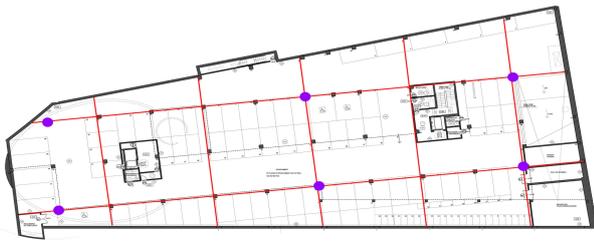


Fig. 9: High Intensity Concept: Neàpolis Building

The FBG-sensors are not able to measure corrosion. On this account it is necessary to choose another kind of sensor. Selected was the Acoustic Emission sensor as the best solution, as explained in section II Sensors. The sensors will be placed on the outer walls of the building. Here corrosion will appear at first. The arrangement of the sensors is, regardless of the intensity concept, constant. This could be added to each intensity level. The placement can be seen in Fig 10, here the orange dots show the placement. This will be a total of 10 AE-sensors.

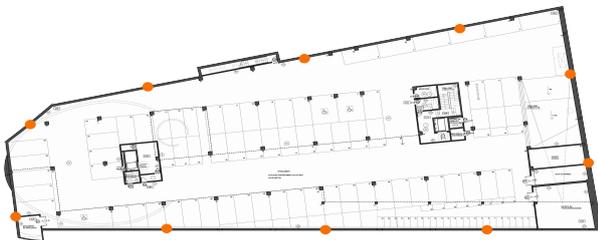


Fig. 10: Corrosion Measurement Concept Neàpolis Building

X. RECOMMENDATION NEÀPOLIS BUILDING

Based on the developed concepts, the intensities were transfer to the floors in the Neàpolis building. It was looked for the forces of weight, environmental influences and the basic structure of the individual floors. In the basement floor are the highest forces of weight. The bearing units emerge the most stress. Therefore the medium intensity was chosen. The building is around eight years old and the occurrence of damages is nearly not existed. Based on the strain in this floor it is necessary to monitor the changes. The only found damage in this floor was corrosion in some parts of the outer walls. It is a useful solution to install the Acoustic Emission sensors on the surface, where the damage was found. By using the medium intensity in connection with the concept of corrosion measurement, a number of 34 FBG-sensors and 6 Acoustic Emission sensors are used. For the ground floor, the same solution is used. There is the stress nearly the same as in the basement floor. The force caused by the weight of the higher floors affects to the structure and the bearing columns of the ground floor. Therefore the medium intensity is also used. Monitoring of corrosion is in this floor useful as well. The ground floor has also contact to earth, where is a great occurrence of humidity. The humidity cause corrosion and some parts of the ground floor are already affected. It is a practical solution to detect corrosion with AE-sensors in the ground floor. The number of Sensors is the same as in the basement floor. 34 FBG-sensors and 6 AE-sensors. The first and the second floor are, contemplating the structure, similar. Therefore it was the same concept for both floors chosen. The force of weight in these floors is less pronounced than in the basement and ground floor. On this account it is not necessary to measure the structure in so many places. For the first and second floor was the low intensity concept chosen. It is the

same for the formation of corrosion. In these two floors is a much lesser occurrence of places with corrosion. The humidity does not move from the ground to the higher floors and rain has not that much influence to cause corrosion. The consequence of this knowledge is that it is not necessary to use AE-sensors in the first and second floor. In the result is that in every floor are 14 FBG-sensors are needed. The third floor has a different structure than the others. It is only a construction on the top of the second floor. The floor has no bearing columns, but outer walls. There is no force of weight, because it is the top floor, which has not to bear other constructions. Because of the low influence forces and also to save money, no one of the called concept will be applied there. The only part that will be monitored is the great steel beam in the ceiling. This is the unit that bears the most loads on the top floor. It is also needless to detect corrosion, for the same reason as in the first and second floor. 6 FBG-sensors are applied in the length of the steel beam.

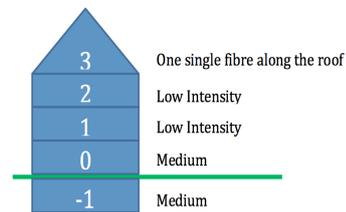


Fig. 11: Recommendation Neàpolis Building

XI. COST-BENEFIT ANALYSIS WITH PURPOSE FORMULA

For the cost-benefit analysis for the implementation plans of the Sant Antoni church and the Neàpolis building a uniform formula has been created. The concept for the formula will exist out of several formulas that determine the parameters of the main formula, where the input can be different for all the different buildings. The formula does not provide a price per m2, but determines the feasibility of Smart Structure systems.

$$\text{Feasibility} = \frac{IC + (SSC + SPMC) \cdot T}{PMC \cdot T}$$

The formula works by dividing the costs for preventive maintenance with Smart Structures by the regular preventive maintenance costs. The outcome gives advice about the feasibility of the Smart Structure system and can also be used to determine a safety rate to the investment in Smart Structures systems. The following can be said about the investment and the feasibility of the investment:

Outcome	Status of Investment
< 1	It is not profitable
1,01 – 1,25	It is profitable, however there is a small margin for errors
1,26 - 1,50	It is profitable
> 1,50	It is a solid Investment

Table 1: Feasibility of Investment

When the outcomes in Table 1 are multiplied by 100% you will get the percentage that will be made in comparison to the traditional preventive maintenance. The percentage is a nice indicator of the profits that can be made with the implementation of the preventive maintenance with Smart Structure systems. The Benefits

Evolution (BE) permits to create graphs to compare the cost of the preventive maintenance without sensors with the preventive maintenance with sensors. We can see the evolution over the time of these two different costs of preventive maintenance. With the two main parts of this formula we get two straight lines and we can deduce the break-even-point. Therefore we need to calculate the time when the Smart Structures begins to save money to compare with the common preventive maintenance.

To calculate this time, we have to consider that the result of the Benefits Evolution is 1, means that this particular year, the costs of the preventive maintenance with and without sensors are the same.

$$\frac{IC + (SSC + SPMC) \cdot T}{PMC \cdot T} = 1$$

$$IC + (SSC + SPMC) \times t = PMC \cdot T$$

$$IC = PMC \times t - (SSC + SPMC) \cdot T$$

$$IC = (PMC - (SSC + SPMC)) \cdot T$$

$$\frac{IC}{PMC - (SSC + SPMC)} = T$$

With this formula the following graph of the break-even-point and the associated cost schedules can be found out.

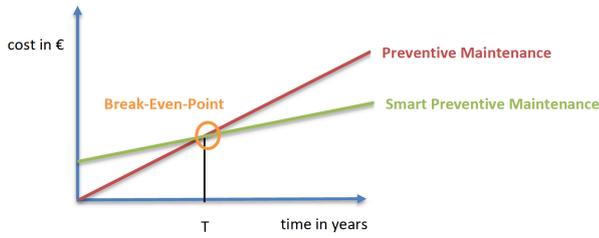


Fig. 12: Break Even Point

Moreover, the way of thinking for this formula is that we are in the prevention of the building, we would like to prevent damages therefore we do not consider a failure.

This formula is expressed in cost (c) and each part is expressed in cost per time ($\frac{c}{t}$).

Legend of symbol:

c	Cost
t	Time
m	Meter
m ²	Square meter

The Initial Costs (IC) defines the introduction cost, which is needed for the beginning, to set up the system of Smart Structures. For that, we have to figure out how many sensors we need and the length of wires for the entire system to deliver the data from the sensors to the central system.

$$\text{Sensors number} \times \text{Sensors cost (c)} + \text{wire length (m)} \times \text{wire cost per meter } \left(\frac{c}{m}\right) + \text{Installation cost (c)} + \text{system to collect data cost (c)}$$

The Smart System Costs (SSC) defines the cost to maintain the system of Smart Structures, all about the components of the Smart Structures system. For example, to renewal of some wires or sensors, which are defect and also the system control checking by a computer engineer.

Renewal System Cost	{	$\frac{\text{New Sensors cost (c)} \times \text{New Sensors Number}}{\text{Lifespan Sensors (t in years)}}$
		$+ \frac{\text{Wires cost per meter } \left(\frac{c}{m}\right) \times \text{wire length (m)}}{\text{Lifespan wires (t in years)}}$
		$+ \text{Installation cost per hours } \left(\frac{c}{t}\right)$
		$+ \text{Inspection Cost of the System per hours (computer engineer)} \left(\frac{c}{t}\right)$

The Smart Preventive Maintenance Costs (SPMC) defines the maintenance costs during the year with sensors. In this case, we use the Smart Structures system consequently and thanks to this system we know precisely where the problem is, such as the beginning of a crack. With this system we save money in the reparations by detecting pathologies in early stages and we also save time and money about the work of diagnostics, made by a civil or building engineer because the system shows easily and fast where the pathologies are located.

To be most realistic as is possible, we thought that this formula of the SPMC depends on the surface in particularly. Is the surface that we have to repair is large, we need more time and consequently money to fix it. Moreover we add in this formula a factor α that represents the evolution of the crack during the time for example. This factor α should be more important for the PMC than the SPMC because without sensors the crack evolution during the time should be faster and

Reparing Cost	{	$\times [(\text{materials} + \text{tools}) \text{cost } \left(\frac{c}{m^2}\right)]$	Financial Loss
		$+ \text{Qualified workforce cost (civil engineer + civil worker) per hour } \left(\frac{c}{t \times m^2}\right)$	
		$+ \text{Downtime cost per hour } \left(\frac{c}{t \times m^2}\right)$	

important than with sensors.

The Preventive Maintenance Costs (PMC) defines the maintenance cost during the year without the sensors. In this case we do not use the Smart Structure system consequently it is complicated to localise the problem precisely. Therefore we spend more time and

Reparing Cost	{	$\times [(\text{materials} + \text{tools}) \text{cost } \left(\frac{c}{m^2}\right)]$	Financial Loss
		$+ \text{Qualified workforce cost (civil engineer + civil worker) per hour } \left(\frac{c}{t \times m^2}\right)$	
		$+ \text{Downtime cost per hour } \left(\frac{c}{t \times m^2}\right)$	
		$+ \text{Inspection cost of the building (civil engineer) per hour } \left(\frac{c}{t}\right)$	

more money than with Smart Structures system because we need more time of a civil engineer or building engineer to diagnose the building regularly.

XII. CONCLUSIONS

The implementation of Smart Structure systems has to do with the size and condition of the building. Each building is different than the other, and this is also the reason why there is not a one uniform formula for the cost of a Smart Structure per m². To get the optimal settings for cost and data collection, for each building there are three different concepts for implementation of Smart Structures. These concepts are; Low, Medium and High intensity. Each next

step of intensity is a more detailed proposal for Smart Structure systems.

The proposed settings for Sant Antoni (1693) church are the Medium intensity FBG-sensor system and a High intensity AE-sensor system. The choice for the medium setting is because the building has been scaled $G=5$ which means it is an average building, with an average amount of pathologies. The medium intensity can give a good overview of the developments of the pathologies in the church. For the corrosion the High Intensity AE-sensor system is chosen, because of the environmental conditions in Vilanova i la Geltrú. The salty air in combination with the wind adds to the corrosion on the church, and to monitor this in detail this system is chosen.

The Neàpolis (2007) building has different intensities on different floors, this has been chosen because of the forces of weight in each floor has a different intensity. Also the environment has been of importance in the choice for the different intensities as can be seen in (Fig. 11). The AE-sensor are added in the basement and the first floor, this is done to find the environmental influence such as; the salty air, the wind and the ground pressure created by the soil on the outer walls of the basement.

For the cost analysis can be determined that a good start has been made, the formula for feasibility is a first draft that shows promising results. Due to the lack of time, and the late retrieval of information a good test was not one of the possibilities however the first check-up with assumed data could be seen as very promising. The formula will be in combination with a grading system for feasibility, this is an indication for the return of investment on Smart Structure systems.

The hypothesis on the feasibility of Smart Structures systems is that it will be beneficial in comparison with the traditional preventive maintenance. This study looks very promising, and with more research on the cost of preventive maintenance with Smart Structures and traditional preventive maintenance the formula can be evolved into a good way for feasibility studies to take place.

XIII. REFERENCES

García, I. and Alegret, J. (2010). Historia y Arquitectura de la Iglesia Parroquial de Vilanova i la Geltrú. Final degree project. Escola Politècnica Superior d'Edificació de Barcelona (Building Engineering). Universitat Politècnica de Catalunya

- [1] Lau, K.-t., Zhou, L.-m., Tse, P.-C., & Yuan, L.-B. (2002). Applications of Composites, Optical Fibre Sensors and Smart Composites for Concrete Rehabilitation: An Overview. In *Applied Composite Materials* (pp. 221-247). The Netherlands: Kluwer Academic Publishers.
- [2] Ruiz, F., & Llorens Garcia, A. (2012). Application of new technologies for structural health management of buildings, Smart Structures. Barcelona: Association of Building Engineers of Barcelona.
- [3] Ruiz, F. (2014). Gravity scale of damages in buildings: from the direct assignment to the statistical contrastation. Doctoral Thesis. Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports de Barcelona (Civil Engineering). Universitat Politècnica de Catalunya
- [4] Soriano Chacón, M. (2013). Advanced assesment methodes for elderly brdiges. State-of-the-art an

- [5] djustification based on LCA. Barcelona. White, N.M., & Boltryk, P. (n.d.). Sensor in Adaptronik. Springer Verlag.