CO-PATCH Report Summary
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Final Report Summary - CO-PATCH (COMPOSITE PATCH REPAIR FOR MARINE AND CIVIL ENGINEERING INFRASTRUCTURE APPLICATIONS)

Executive Summary:

The basic concept of the present work is the definition of an effective repair method for large steel structures with defects. Two basic steel structural types were dealt with in this work, namely marine structures and steel civil engineering structures. The basic objective of this project was to demonstrate that composite patch repairs can be environmentally stable and therefore, that they can be used as permanent repair measures. This objective was achieved by:

• Establishing a very strong forum of external stakeholders, which demonstrated that both the Marine and Civil Engineering industries recognise that Co-Patch technology is a viable repair technique, providing asset owners with very large cost reductions and reduced operational downtime.
• Studying and demonstrating through theoretical analyses, extensive and advanced numerical simulations and a very large experimental testing programme that the use of composite patch repairs leads to the reinforcement of a steel structural member.
• Determining, evaluating and quantifying the efficiency of composite patch reinforcements in the marine/bridge environment, in both short and long term through static and fatigue tests in both conventional and artificially aged specimens.
• Determining practically applicable, sensor based monitoring techniques of the final through-life structural integrity of the patch.
• Identifying proper surface preparation methods and lamination conditions and quantifying the beneficial effect of the patch reinforcement on the static strength and on the fatigue life prolongation.
• Developing guidelines for the effective finite element modelling of a patched structure.
• Developing a generalized procedure for the design and application of composite patch reinforcements in steel marine and civil engineering infrastructure applications.
• Producing patch design for typical repair cases.
• Demonstrating the effectiveness of the developed design tools and procedures through full-scale tests.
• Developing an internationally recognised training programme for personnel.

The proposed composite patch repair technology is an innovative and highly competitive product that caters for the needs of both marine vessels and civil engineering infrastructures. It reduces quite significantly the maintenance costs of many large steel structures, and in the case of metallic bridges it prolongs their design life. The proposed technology creates a new market and it gives the partners the capability of providing high technology and high added value services worldwide.

Project Context and Objectives:

In January 2010 a consortium of 15 SMEs and RTDs from eight European countries initiated a three year European (FP7) funded
project on Composite Patch Repair for Marine and Civil Engineering Infrastructure Applications – CO-PATCH. This is a novel effective repair and/or reinforcement method for large steel structures with defects. Two basic steel structural types are dealt with in this work, namely marine structures (primarily ships) and steel civil engineering structures (e.g. bridges). Many of the major problems that these structures face during their operational life are common, with fatigue playing a predominant role among them. Repeated loading is a very common loading condition for both these structures, which, in areas of stress concentrations, leads to the initiation and growth of fatigue cracks. These cracks, if not detected and properly repaired in time, can grow to critical lengths and result in catastrophic structural failures. An additional structural problem of either marine or other large steel structures is corrosion, particularly for vessels and structures designed with thinner plating due to the use of high-strength steels. Corroded plating or beams jeopardise the strength and stiffness of the structure and measures have to be taken to reinstate the original structural characteristics. Besides the above two major defects of the steel structures, there is often the need for upgrading the strength and/or the stiffness of a structure, enabling it to face new loading conditions or helping in mitigating initial design deficiencies.

The traditional ways to deal with such problems are well known. Fatigue cracks in welds or panels usually involved renewal of part of the weld, welding in the cracks in a panel or replacement of the whole parent panel itself. The standard way to face heavy corrosion was also the replacement of the corroded structural members, whereas the use of bolted or welded doubler plates seemed to be the only way until now to reinforce a structural part. There are circumstances, however, when these repair or reinforcement approaches are either time-consuming and costly, or simply impossible to be followed.

Composite patch repairs and/or reinforcements overcome many, if not all the aforementioned disadvantages of the traditional methods. More specifically:

• They do not involve hot works in any way and, therefore, existing deadweight loading or proximity to explosive environments has no particular consequences.
• Patches can be applied directly on corroded steel members after performing a relatively straightforward surface preparation, thus removing the need for replacement.
• They can be completed faster.
• They exhibit good fatigue resistance.
• They do not cause stress concentrations.
• They result in low added weight.

All these innovations reduce significantly the cost and the time of the repair or reinforcement.

Composite patching has proven its effectiveness and cost benefits by its application in the aerospace industry for several years now, since there are already several thousands of operating patches in various aluminium aircraft structural parts. However, there are several fundamental differences between the aerospace applications and bridge/marine/offshore steel applications, which dictate a separate approach and investigation of the problem. Furthermore, there are big differences between what is widely accepted as normal repair cost in an aerospace structure and its steel marine/bridge counterpart.

The objective of this project is to demonstrate to all stakeholders that composite patch repairs or reinforcements can be environmentally stable and therefore, that they can be used as permanent repair measures on steel marine structures and steel civil engineering infrastructure applications. This objective will be achieved by:

• Studying and demonstrating through theoretical analyses, numerical simulations and experimental testing, that the use of composite patch repairs leads to the reinforcement of a steel structural member, either by increasing its load carrying capacity, or, in the case of a defected structural member, by reinstating its structural integrity.
• Establishing a stakeholders’ forum to discuss and agree the business and regulatory implications of introducing composite patch repairs.
• Determining, evaluating and quantifying the efficiency of composite patch reinforcements in the marine/bridge environment, in both the short and long term, via an understanding of material degradation modes and their impact on mechanical properties and structural integrity of the steel-to-composite system.
• Developing proper numerical modelling procedures for modelling a composite patch reinforced structure and by drawing out general guidelines for performing such numerical simulations.
• Developing a generalized procedure for the design of composite patch reinforcements in steel marine and civil engineering infrastructure applications, leading to the selection of the proper surface preparation techniques, adhesives, reinforcing composite material, configuration (number of layers, stacking sequence), geometry of the reinforcement, etc.
• Evaluating existing or developing new, practically applicable and sensor based monitoring techniques of the initial quality and the final through-life structural integrity of the patch.
• Providing pre-designed, ready-made composite patch solutions for repairing or reinforcing standard problematic cases of a steel marine or civil engineering structure.
• Developing best-practice generalized procedures for the application of composite patch repairs, which could be followed in-situ by properly trained personnel and which could finally lead to the classification of composite patches as permanent repairs.
• Demonstrating the effectiveness of the developed design tools and procedures through full-scale tests of patch repaired structures.
• Disseminating the results of the project to the corresponding administrative bodies (i.e. maritime authorities, railways or highways authorities, port authorities, etc.) to secure their acceptance of the composite patches as permanent repair solution.
• Developing an internationally recognised training programme for personnel including examination and certification.

Project Results:

The main scientific and technological results that were produced from the Co-Patch activities are listed below, following the overall project work flow.

• A very strong forum of stakeholders was established, which was comprised of many, very active, external members. The forum demonstrated that both the marine and civil engineering industries recognise that Co-Patch technology could be a viable repair technique.
• Furthermore, it has been demonstrated that asset owners are very interested in being able to use Co-Patch technology. In particular, the marine companies of the forum became aware that there is a need for approval by Class and Statutory bodies for use of the technology, while the civil sector companies are not restricted by such needs for approvals. The feedback from both marine and civil members demonstrated that Co-Patch technology could provide asset owners with very large cost reductions and reduced operational downtime. Industry is ready to accept the technology when proved effective and acceptable to approval bodies.
• The regulatory framework for both marine and civil engineering applications was defined. This is a very crucial step towards the targeted acceptance of the Co-Patch technology by the authorization bodies, especially for the marine sector.
• The possibility of the patch repairs to be classified as of a permanent type was examined. It was concluded that Co-Patch technology could be a viable, cost effective and permanent alternative to traditional repair methods.
• A special inspection procedure for damaged steel structure tailored to the requirements of patch repairs was developed. The procedure enables the inspector to decide if the examined structure can be a successful candidate to be repaired by the Co-Patch method. Comparing the new procedure against the usual inspections, the inspector has to perform additional tasks, to accommodate the special requirements of a composite patch repair. These special tasks have been described and a pertinent checklist has been produced, to guide the inspector through the required process.
• Furthermore, procedures and methods were developed, allowing the design of a quality assurance plan for a specific patch production system, after the decision for the applicability of a particular patch repair has been made. By following these procedures, a reliable patch application can be designed and applied.
• Once the patch has been applied, four non-destructive test (NDT) methods were found to be the most useful, namely, the BondMaster device (acousto-ultrasound technique), electrical strain gauges, Fibre optical Bragg Gratings (FBG) and Optical
Back scattering Reflectometer (OBR). In addition to the above, ultrasound (Pulse-Echo technique applied on the patch side), radiography and acoustic emission can also be used as reference measurements of the crack growth. Description on how to use these methods, as well as their advantages and disadvantages, has been given in the project reporting. All methods were thoroughly tested both in the laboratories and in the field.

- The project work concluded that the aforementioned most promising NDT methods can be also well suited for automated monitoring. Especially for the BondMaster method it was proved that it would need significant refinement, thus it is currently better suited for periodic inspection. The remaining methods can be successfully used for automated and continuous monitoring. Today the technology is available only for strain gauges. It can also be extended to include FBGs. The OBR method can in principle be automated, but it would be very expensive with today’s equipment.

- Several steel surface treatment methods were examined for their appropriateness to be used prior to the patch application. Among them the needle gun surface treatment proved completely inappropriate since, in most of the cases, the patches debonded right after manufacturing or during handling before the tests.

- The influence of the environmental parameters on the performance of the patch repairs was examined through extensive testing of patched samples exposed to the effect of environmental chambers. Ageing proved to have a deteriorating effect on the static strength of unpainted patched specimens. On the contrary, properly painted specimens were not seriously influenced by ageing.

- The results of the extensive laboratory testing demonstrated that the yield strength of the cracked patched specimens was found to be significantly increased with respect to the values of the unpatched plates, by a multiplication factor ranging from 2.3 in the case of non-aged specimens to 1.6 in the case of aged, not properly protected ones.

- Regarding the repair of corroded steel plates, it was proved that a properly painted patch fully reinstates the strength of the structure, withstanding also the environmental loading of ageing. The experimental campaign on civil sector specimens demonstrated also that properly applied pre-preg patches on defected beams subjected to bending loading reinstate both the stiffness and the strength of the defected beam to levels even higher than those of the original non-defected beam.

- Regarding the fatigue life of the patched steel plates, it was increased by a factor of approx. 5 compared to the fatigue life of similar cracked, unpatched plates, for the case of grit blasted specimens with a vacuum infused patch.

- The optimum design of a patch to be applied on defected structural details of common geometry was elaborated and best results were obtained with a patch fibre orientation of 0º with respect to the direction of load application.

- Composite patch repair can be beneficial in delaying crack growth in civil engineering applications girders with fatigue cracks. As it’s the case in marine applications too, it was shown that the sooner the patch is applied, the better improvement of the fatigue life is accomplished.

- Web breathing has also been investigated and FRP bonded repair – using stiffeners – is showing great promise; it could have major advantages compared to over-plating or additional welded stiffeners.

- Regarding the numerical assessment and the calculation of the strength of a Co-Patch repair, various finite element modelling techniques of the patch/metal joint were studied and investigated and the corresponding FE models were developed for both static and cyclic fatigue loading involving crack propagation under the patch. Regarding the latter problem, VCCT method demonstrated several advantages with respect to the J integral method.

- The experience and know-how obtained from the simulations of the laboratory tests and the performed parametric study were collected and presented as numerical modelling guidelines for this type of problems.

- One of the most important results of the project was the development of best practice design guidelines and application procedures, which describe the appropriate use of the involved techniques, provide guidance for the structural design of the patch, provide guidance for the correct implementation of composite patches and promote the use of composite patches as repair/reinforcement of metallic structures. These guidelines mirror the four principal stages of a composite patch repair, namely the evaluation of damage, the patch design, the composite patch application and the repair monitoring. In parallel, two important aspects are also included in the guidelines, namely the regulatory framework which constitutes a special issue on ships, and the recommended personnel training for an optimum patch application.

- Special prototype patch designs were produced for the following five typical repair cases: (a) reinforcement against buckling of the cross deck plating of a bulk carrier, (b) repair of cracks at the edges of man holes or lightening holes at floors, girders or swash bulkheads of the ship structure, (c) repair of cracks at the stiffener cut-outs in double bottom or web frame floors, (d)
repair of cracks at the bracket toe in connections between stiffeners, and (e) repair of cracks and/or reinforcement against buckling at either the flange or at the webs of civil engineering applications large girders.

- Full-scale tests demonstrated that composite patches, if applied properly and following the developed guidelines, can operate in the real marine environment for long without any problems. It was experimentally shown that patching is a viable and effective solution, decreasing the stress levels at the areas where they are installed.
- Three different options for continuously NDT monitoring the patched structure response demonstrated their effectiveness and viability through the full-scale tests.
- A training program framework to meet the requirements for European accreditation in the welding and joining field and an application for CSWIP (Certification Scheme for Welding and Inspection Personnel) certification for course approval has been created and then officially submitted to support the use of Co-Patch technology. The framework has been defined in two levels. The first (highest) level has been embedded within the CSWIP application to clarify the key areas that require to be covered by the examination required for certification. The second level document takes the areas defined in the first level and expands them into a course syllabus defining where possible the sources of appropriate material that is either readily available or that will be require to be developed.

Potential Impact:

The expected final results of the project are the development of guidelines for the proper numerical modelling of a composite patch reinforced structure, the development of a generalized procedure for the design of composite patch reinforcements, the development of best-practice generalized procedures for the application of composite patch repairs, the demonstration of the effectiveness of the developed design tools and procedures and the development of an internationally recognised training programme for personnel.

The proposed composite patch repair technology is an innovative and highly competitive product that addresses both marine vessels and civil engineering infrastructures such as steel bridges. It reduces quite significantly the maintenance costs of many large steel structures, in many cases being the best financially feasible way to prolong the operational life of bridge type structures (e.g. actual bridges, cranes, etc.). A new market is created by the proposed technology, giving the participating companies the capability of providing high technology and high added value services worldwide. This market is directly related and supports the existing European shipbuilding and ship-repair industry. Being in line with the tradition of European shipyards which are world market leaders in terms of turnover innovative products and processes, the proposed technology creates the environment for improving Europe’s competitiveness in specialized and advanced repair works, by increasing the number of solutions for repair and rehabilitation of large steel structures. The use of innovative repair solutions will enhance the productivity and efficiency (reduction of time and costs) of the EU repair industry, contributing also to the creation of more attractive working conditions. At the same time, the composite patch repair technology creates new job opportunities in two sectors. First for engineering consultancy enterprises which can become active in the design of such repairs and/or reinforcements and, second, for highly skilled personnel with expertise in composite materials and their fabrication methods, who will apply the patches. A flying crew consisting of a few skilled technicians can provide this type of specialized service worldwide and in a very short time. One of the objectives of the project is oriented towards this goal that is to develop off-the-shelf, ready-made patch solutions for some standard cases that need repair or reinforcement.

The main dissemination activities carried out by the project partners are summarized in the table below:

Co-Patch web site

A project website (www.co-patch.com) was designed and created by WP leader TWI, publicising the project aims and objectives and listing the consortium partners. This website has been a very useful tool throughout the project for all partners and stakeholders to share and access to all the information and results generated by Co-Patch on a regular on-going basis. It has been also useful tool to recruit new stakeholders.
Partners' web sites

Through their own websites, many of the partners have publicised the project via creation of links to the Co-Patch website, new sections especially dedicated to the project and also internal newsletters and articles.

Press releases and publications

Over 30 articles promoting the project content and aims were published through relevant industry sectors technical press, including RINA, NGCC, NAFTAK, UK Materials KTN-FOCUS, through regional general press, as well as via the partners' well established network of contacts and clients. The Co-Patch consortium has worked extremely well in disseminating and publicising the project. The publicity gained by publishing a number of articles through the various means mentioned above has, as a consequence, enabled the consortium to receive a large amount of interest from 27 organisations including asset owners, technical institutes and repair contractors (i.e. Network Rail, Grimaldi Group, Amber Composite, London Underground, Highways Agency, etc.) requesting their participation as stakeholders in the project.

Conferences, papers and presentations

Over 14 papers have been published in scientific journals and in scientific conference proceedings. Several papers are also currently in progress to be submitted after the end of the project. The Co-Patch consortium has worked extremely well with regards to the dissemination activities by attending/organizing meetings and conferences with relevant organisations such as technical institutes and repair contractors and by presenting papers and posters. In addition several Co-Patch relative PhD and Master Theses have already completed or they are progressing at the university partners of the consortium (NTNU, NTUA and UniS).

Newsletter

Three project newsletters have been published over the project duration. The first annual newsletter was created and published by TWI following project's annual meeting in Paris in January 2011. The second newsletter followed the 5th PSC meeting in January 2012 and the third one was published in May 2013 after the last stakeholders workshop held in London. The newsletters (http://www.co-patch.com/publication/) contained updates on the project achievements and progress/information about the involvement of technical partners and stakeholders. Several additional newsletters dealing with Co-Patch were published by some of the partners.

Co-Patch Stakeholders Forum and Workshop

Two stakeholders meetings took place during the project, attended by several companies and organizations. These forums demonstrated that both the Marine and Civil Engineering industries recognise that Co-Patch technology could be a viable repair technique. Furthermore, they showed that asset owners are very interested in being able to use Co-Patch technology. The feedback from both marine and civil members demonstrated that Co-Patch technology could provide asset owners with very large cost reductions and reduced operational downtime. Industry is ready to accept the technology when proved effective and acceptable to approval bodies. A final Co-Patch workshop also took place at the end of the project. The event was extremely successful with a number of areas identified for potential development after the completion of Co-Patch.

Regarding exploitation activities, at the beginning of the project the consortium was more focused on dissemination activities to recruit stakeholders and foster the aim of the Co-Patch technology. After 6 months and throughout the project period, TWI supplied guidelines that could be adapted to each partner (company or university) for the application of the implemented technology. Then TWI contacted each partner individually to determine how they have planned to grow and develop their
activities/business compared to the guidelines given.

As might be expected, universities were not so proactive in exploiting results commercially in comparison to companies, but alternative approaches were adopted. Academic partners have worked on introducing the knowledge gained into their higher degree academic syllabus and, in relation with the project, have created PhD and Masters positions and have also planned to integrate adhesion/patch repairs lectures related to the Co-Patch project in different classes.

The SMEs have used the knowledge gained from Co-Patch to develop new technologies and new networks or businesses. In many cases they will directly use the benefits and outputs from Co-Patch to develop business within the civil and marine sectors.

The R&D organisations are using the benefits of the Co-Patch project for consultancy and to provide a patch application support service to the marine and civil sectors through the development and ultimately the delivery of training courses in Europe based upon the development of an internationally recognised training program framework for personnel by TWI.

List of Websites:

The project started on 1 January 2010 and ended on 30 April 2013. The project web site is www.co-patch.com and contact can be made at either contactus@co-patch.com or by contacting the project coordinator Assoc. Professor Nicholas TSOUVALIS at tsouv@mail.ntua.gr.

Related information

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