

## Seismic Retrofit of St. Joseph Hospital Using Advanced Composite Materials for the Enhancement of Column, Slab, Wall and Beam Elements

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**ABSTRACT:** St. Joseph Hospital, in Orange, California, is one of hundreds of hospitals in the state with buildings built before 1973, that have been classified as Structural Performance Category 1 (SPC-1) as defined by Senate Bill 1953 (SB 1953). SPC-1 buildings are those that are considered hazardous and at risk of collapse or significant loss of life in the event of an earthquake. Two buildings at the facility will receive a SPC-2 upgrade based on a nonlinear analysis and specific design criteria for the use of fibre reinforced polymers (FRPs). The advanced composite materials were used for a variety of structural deficiencies, including, column shear, diaphragm shear, wall shear, diaphragm chords, collectors, shrinkage joint shear transfer and life safety catch mechanisms. The FRPs were selected in order to minimize disruption to the operating facilities and provide the most cost effective design solution. In order to be accepted by the Office of State-wide Health, Planning and Development (OSHPD), a strict specification and design criteria had to be reviewed and accepted. This paper will review the analysis of the buildings, the submittal requirements and the construction details implemented to complete the SPC-2 retrofit in accordance with State law.

### 1 INTRODUCTION

In September of 1994, Senate Bill 1953 (SB 1953) was passed as an amendment to the Alfred E. Alquist Hospital Seismic Safety Act of 1983 (Alquist Act), which provided regulations for essential facilities such as hospitals to remain operational after an earthquake. Hence, the building provisions and regulations of SB 1953 were developed to ensure that general acute care hospital buildings would remain intact and continue operations and provisions of acute care medical services after a seismic event. Under the provisions, general acute care hospital owners were required to perform seismic evaluations to determine the buildings' performance rating in both the Structural Performance Category (SPC) and Non-structural Performance Category (NPC). The regulations not only classified the structural performance of the buildings to seismic events but set deadlines for the necessary renovations to be completed, otherwise, acute care services would no longer be provided in the buildings.

There are approximately 270 general acute care hospital facilities including 2,700 hospital buildings that have been impacted by the provisions in SB 1953. Through the classifications, buildings with a SPC-1 rating are considered hazardous and at risk of collapse or significant loss of life in the event of a major earthquake. These buildings are required to be retrofitted to either SPC-2 or SPC-5.

The analysis of buildings to determine their SPC rating can be conducted by multiple methods. According to the 2001 California Building Code (CBC), engineers are allowed to use the so-called "Method B" or advanced analysis approach such as Nonlinear Static Procedures (NSP) for seismic analysis of buildings. The use of procedures in FEMA 356 (2000) Pre-standard for Seismic Rehabilitation of Buildings with some modifications was considered an acceptable approach to implement Method B. Nonlinear static procedure (NSP) or pushover analysis is believed to provide

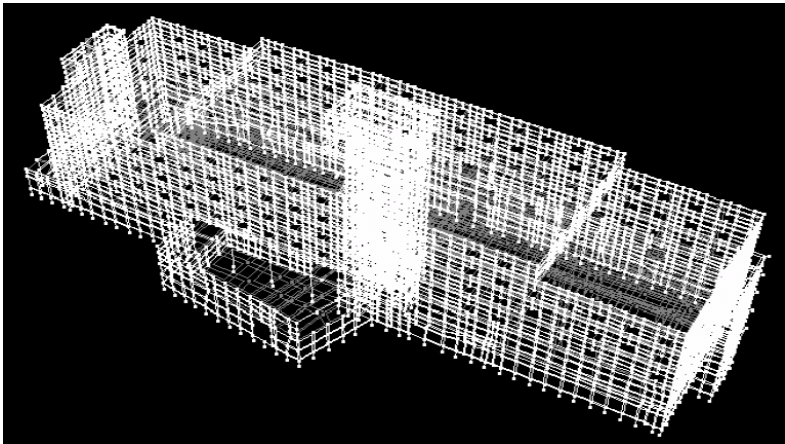
adequate information on seismic demands imposed by the design ground motion on the structural system and its components.

This study focuses on two low-rise hospital buildings located in Orange County, California. The buildings were constructed in the early 60's with a reinforced concrete shear wall system and are non-compliant buildings per 2001 CBC. In order to meet the code requirements of SPC-2, both buildings was analysed and retrofitted based on the results from nonlinear pushover analysis using the Tyfo® Fibrwrap® Systems by Fyfe Company. By implementing this advanced analysis approach, structural performance was better understood which led to a more efficient use of the composite retrofit methods. Details of the nonlinear static procedure implemented in the larger building are described below.

## 2 NON-LINEAR STATIC PROCEDURE FOR SEISMIC ANALYSIS

The Non-linear Static Procedure (NSP) is intended to provide a simplified approach for directly determining the nonlinear response of a structure at different levels of lateral displacements from elastic response through the development of a failure mechanism. The practical objective of nonlinear seismic analysis methods is to predict the expected behaviour of the structure in the seismic events.

In the analytical model, only the primary lateral force resisting system (LFRS) of this building, which is reinforced concrete bearing walls, were modelled using Perform-3D (Computer & Structures 2006). Four-node quadrilateral elements were used to model reinforced concrete wall components, for instance, piers and spandrels. Beams and columns supporting discontinuous walls were modelled using frame elements with nonlinear hinges at both ends. Diaphragms were explicitly modelled using four-node quadrilateral elements. Seismic masses were proportionally distributed on the diaphragm. Continuous wall footings were modelled using nonlinear compression-only strut elements to simulate soil-structure interactions. Figure 1 shows a three-dimensional analytical model in Perform-3D.



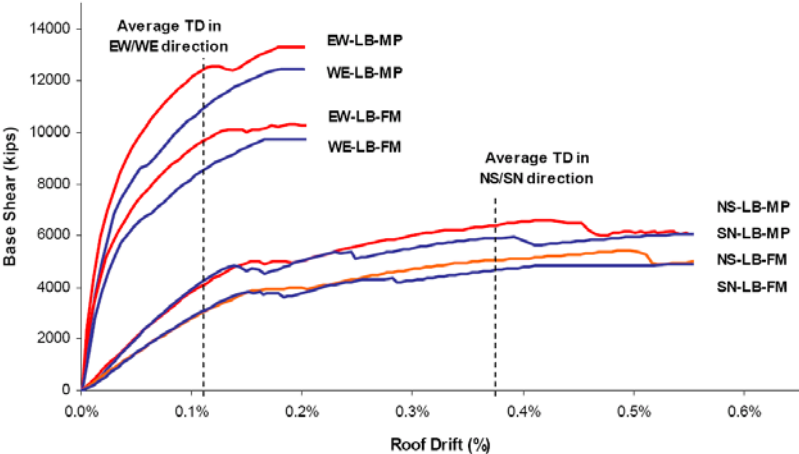
**Figure 1. Perform 3-D nonlinear model of the building.**

Modified Kent-Park stress-strain relationship (Kent and Park, 1971) was implemented in the nonlinear concrete modelling. Elasto-plastic stress-strain relationship was used for the modelling of reinforcement. Typical nonlinear load deformation relationships recommended by FEMA 356 were used to model nonlinear shear behaviour in reinforced concrete piers and spandrels, and nonlinear plastic hinges of beams and columns. Diaphragms were modelled elastically as they were expected to remain elastic. During the course of analysis, if the diaphragm demands exceed the diaphragm capacity, inelastic materials was planned to be used to capture the actual diaphragm behaviour and force distributions.

In order to achieve the performance-based design objectives, inelastic behaviour of each component was limited to the target building performance level which translated to the acceptable criteria. “Life Safety”, which is equivalent to SPC-2, was the target building performance level of this building and the associated acceptance criteria of each structural component recommended by FEMA 356.

Gravity loads were applied on the primary lateral force resisting system. Self-weight of walls, beams and columns were included as part of gravity loads. Two vertical lateral load distributions were used as recommended in FEMA 356, i.e., mass-proportional (MP) and fundamental mode (FM). The intent of dual lateral load patterns is to bind the range of design actions that may occur during the actual dynamic response.

Figure 2 illustrates pushover curves and average target displacements associated to each orthogonal direction. The results show that this building potentially has greater deformation capability in North-South direction than East-West direction.



**Figure 2. Pushover curves for mass-proportional and fundamental mode.**

Based on the analysis results, several retrofit methods were investigated to achieve the target structural performance level and preferred building mechanism. Eventually, the ultimate goals were to retrofit this building with the most cost-effective and least invasive method, and minimal disruption of hospital operations.

**3 OSHPD SUBMITTAL REQUIREMENTS**

The Office of State-wide Health, Planning and Development (OSHPD) oversees all acute care centre renovations and new construction in the state of California. The planning of these developments requires a thorough design and review of each structural deficiency to be addressed. Specific to St. Joseph’s Hospital, it was determined that the facility had multiple structural deficiencies stemming from seismic forces. Ultimately, using fibre reinforced polymers (FRP) from Fyfe Company was the best repair method due to scheduling, cost-effectiveness, previous structural testing of the required applications and the level of experience of the company with FRP installations on acute care centre building retrofits under OSHPD jurisdiction.

The FRP acceptance by OSHPD depended on thorough evaluation of the composite systems for every structural element to be strengthened. These requirements consisted of five necessary submittal requirements: the design criteria, design guidelines, FRP calculations, FRP details, and finally the FRP specifications. The design criteria outlined the approach of the FRP design as per relevant FRP codes and guidelines and defined the method of analysis to determine any structural deficiencies. The design guideline outlined details of the specific structural elements to be retrofitted. The guideline defined the type of element being strengthened, the reason for the strengthening, the type of composite materials to strengthen the element and other FRP installation requirements such as finishes. The FRP calculations determined the final FRP design, including the material required and number of layers, which were depicted in the FRP details. The details also indicated the locations, FRP orientation, and numbers of layers used on each structural element to receive composite. Finally the FRP specifications were provided to meet all OSHPD application, testing and quality control standards. These five documents were submitted for every structural element to ensure proper documentation of all work.

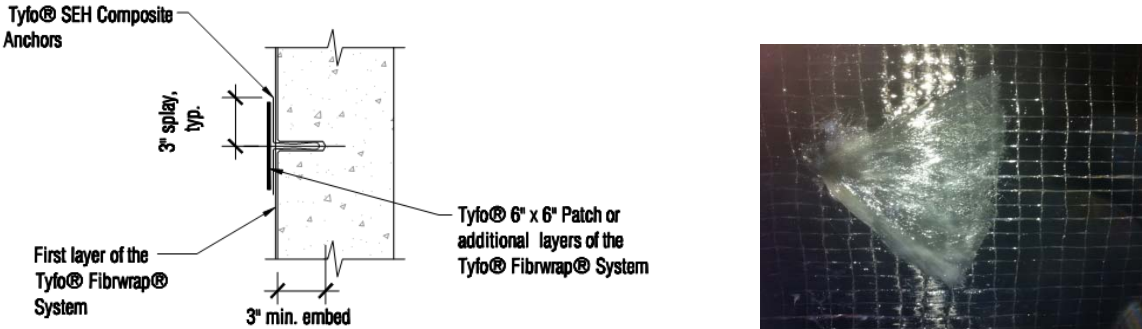
**4 FIBRE REINFORCED POLYMER SYSTEMS**

**4.1 Tyfo® Fibrwrap® Systems**

One main deciding factor in using FRP composite systems from Fyfe Company was due to the level of testing of these materials. The Tyfo® Fibrwrap® Composite Systems have been tested extensively at various universities and laboratories and have been installed in thousands of structures throughout the world. These systems have met rigorous testing and quality control requirements to be considered synonymous with building materials such as concrete and steel. These requirements were also part of becoming compliant with the International Building Code and obtaining an Evaluation Service Report.

The fibre reinforced polymer materials used for the St. Joseph’s Hospital retrofit included the Tyfo® SCH-41, Tyfo® BCC and Tyfo® SEH-51A Fibrwrap® Composite Systems along with standard Tyfo® SEH Composite Anchors. These Fabrics were joined with the Tyfo® S Epoxy in unique combinations to provide tension capacity to the required reinforced concrete elements.

The Tyfo® SEH Composite Anchors were used in many of the details to mechanically fasten the composite sheets into the structural elements. The composite anchors are made of continuous glass fibre bundles and saturated using the Tyfo® S epoxy. The anchors were installed in the concrete to a minimum specified embedment length and splayed out over the FRP sheets (between the first and second layers) to anchor the composite material and enhance tension development into the substrate. The SEH composite anchors had a diameter of 0.25-inch (6.4 mm), 6-inch (152.4 mm) total length, and installed at a 3-inch (76.2 mm) minimum embedment at every free edge on all bond critical applications per OSHPD’s detailing requirements. See Figure 3 for a typical application detail of the Tyfo® SEH Composite Anchor.



**Figure 3. An installation detail of the Tyfo® SEH Composite Anchor is shown on the left. Actual Field Installation is shown on the right.**

The Tyfo® SCH-41 unidirectional systems and the Tyfo® BCC bi-directional systems installed were both carbon fibre composites while the Tyfo® SEH-51A unidirectional systems and SEH composite anchors were glass fibre composites. This project included a combination of these various composite systems for the seismic retrofit of St. Joseph’s Hospital. The design properties of the composite systems are listed in Table I.

**Table I. Design Properties of the Tyfo® Fibrwrap® Systems**

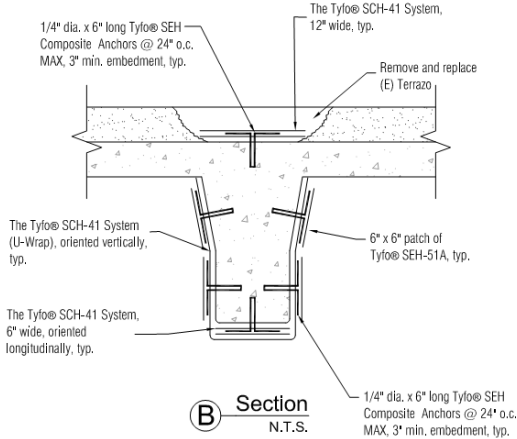
	<b>Fabric Architecture</b>	<b>Tensile Strength ksi (MPa)</b>	<b>Tensile Modulus psi (GPa)</b>	<b>Elongation (%)</b>
<b>Tyfo® SCH-41</b>	Unidirectional	121 (834)	11.9 x 10 <sup>6</sup> (82)	0.85
<b>Tyfo® SEH-51A</b>	Unidirectional	66 (460)	3.03 x 10 <sup>6</sup> (20)	1.76
<b>Tyfo® BCC</b>	Bidirectional (±45)	81 (558)	5.9 x 10 <sup>6</sup> (40)	1.19

All exterior surfaces that received the composites were finished with an exterior grade paint to improve aesthetics and provide additional UV protection. The interior-wrapped surfaces were finished with the Tyfo<sup>®</sup> RR coating to comply with a class 1 flame and smoke rating per ASTM E-84. The various structural deficiencies including, column shear, diaphragm shear, wall shear, diaphragm chords, collectors, shrinkage joint shear transfer and life safety catch mechanisms were all addressed and retrofitted using a combination of these Tyfo<sup>®</sup> Fibrwrap<sup>®</sup> Systems.

Fibrwrap Construction was the certified applicator of the composite systems at St. Joseph’s Hospital. The importance of the certified applicators was critical due to the amount of work and complexity of the installation. With any structural repairs, the composite advantages depend heavily on the proper installation to ensure system performance and retrofit lifespan. Both the bid documents and the quality control manual referred to in ICC-ESR 2103 required that the contractor installing the composite be trained and certified by the manufacturer. The complexity of this project proved challenging but was completed on time and within budget.

**4.2 Beams**

Reinforced concrete beams were strengthened with the Tyfo<sup>®</sup> SCH-41 System for positive and negative flexure. The beams were also reinforced for shear enhancement. The Tyfo<sup>®</sup> SCH-41 fibre was used to supplement the top steel and enhance the negative moment capacity while the bottom steel was supplemented to enhance the positive moment capacity. Likewise, transverse fibre was used to enhance the shear capacity of the beams. Tyfo<sup>®</sup> SEH Composite Anchors were installed along the free edges of the beam for additional anchorage. The composite anchors were sandwiched between layers of FRP (between the first and second layers). The same beam applications also required a two-hour fire rated assembly per ASTM E-119 due to the fact that the applications were for gravity loads (as opposed to seismic). This requirement was fulfilled with the four-component, spray-applied Tyfo<sup>®</sup> AFP (Advanced Fire Protection) UL assembly. The system was installed over the composite at a minimum thickness of 0.75-inch. See Figure 4 for the beam repair detail.



**Figure 4. Beam reinforcement detail using the Tyfo<sup>®</sup> SCH-41 system and the Tyfo<sup>®</sup> SEH Composite Anchors. The 2-hour rating was provided with the Tyfo<sup>®</sup> AFP System.**

**4.3 Columns**

Columns were retrofitted with the Tyfo<sup>®</sup> SEH-51A System. The wraps were applied in the hoop direction to supplement the transverse steel reinforcement, to increase the shear capacity of the columns and to provide plastic hinge confinement. Figure 5 depicts the installed unidirectional GFRP material.



**Figure 5. The Tyfo<sup>®</sup> SEH Composite System installed over a square column.**

#### 4.4 Walls

Multiple wall elements were retrofitted with the Tyfo<sup>®</sup> SEH-51A System and Tyfo<sup>®</sup> BCC System for in-plane shear enhancement as well as panel-to-panel shear transfer. Spandrel beams were also retrofitted; the composite was applied around the spandrel beam to act as a life-safety catch mechanism over doorways (Figure 6). This was used to provide protection against concrete spalling and reduce the potential for bodily injury. Essentially any damage to the concrete that could occur during a seismic event would be contained by the composite.



**Figure 6. Spandrel walls over doorways were wrapped with the Tyfo<sup>®</sup> SEH Composite System to act as a life safety catch mechanism during seismic events.**

Wall elements were also strengthened with horizontal fibre to add shear strength. Weakened plane joints were retrofitted with the Tyfo<sup>®</sup> BCC Bi-directional Carbon Fibre System to provide panel to panel shear transfer (Figure 7).

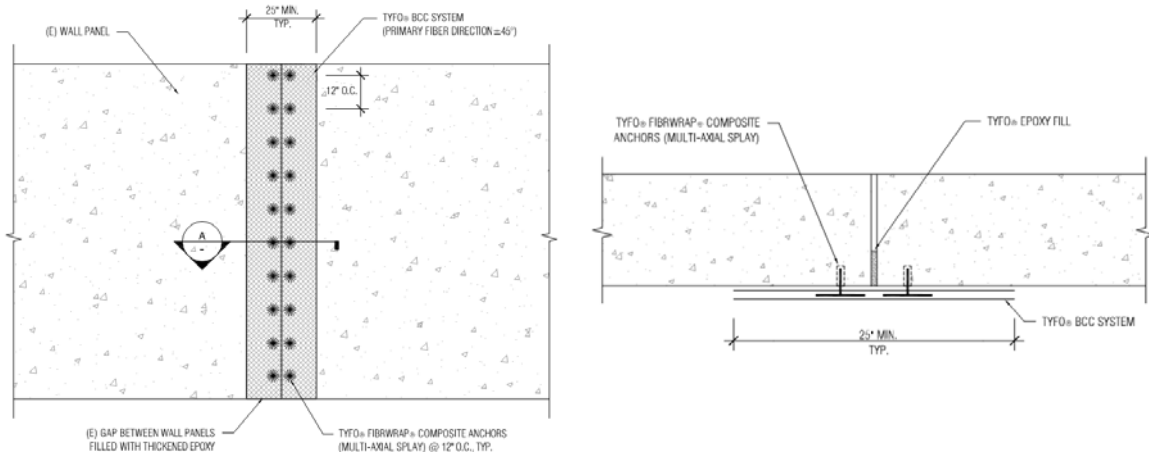


Figure 7. Weakened plane joints retrofitted with the  $\pm 45$  bidirectional Tyfo® BCC System.

Finally, diaphragm chords are intended to be retrofitted by adding fibre horizontally to the edge of the slabs from the exterior of the building. In this application, the installation will be conducted to the exterior face of the building as seen in Figure 8. By supplementing the longitudinal steel reinforcement, the diaphragm flexure capacity will be enhanced.

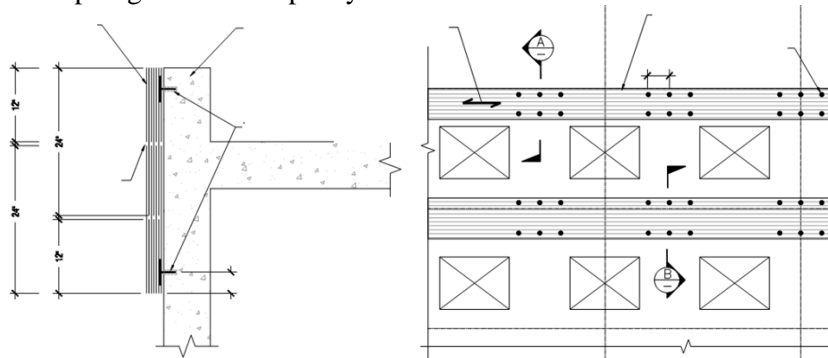


Figure 8. Diaphragm chord elements will be retrofitted with the Tyfo® SCH-41 System.

#### 4.5 Slabs

Slab elements including were retrofitted for both diaphragm shear and tension (collectors). In the collectors, the fibre was added to transfer seismic forces from one side of the building to the other (from shear wall to shear wall). For the slab systems, the FRP was used to strengthen the slab in both directions to enhance the horizontal diaphragm shear capacity in both directions. This is seen in Figure 9 below.

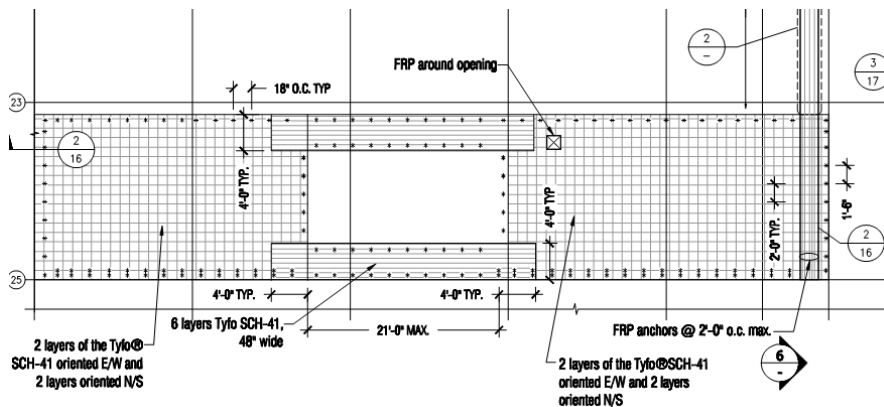


Figure 9. Slab strengthening with the composite system oriented in both directions.

## 5 CONCLUSIONS

St. Joseph's Hospital is one of many hospitals affected by Senate Bill 1953. After analysis of the hospital facility using nonlinear static procedure, a number of buildings in the hospital were determined to be classified as SPC-1 and considered hazardous and at risk of collapse or significant loss of life in the event of an earthquake. From the analysis, multiple structural deficiencies were discovered and it was concluded that fibre reinforced polymer composites would be the optimal solution to address the majority of these deficiencies in a timely, non-destructive and cost-effective manner. The hospital has undergone and continues to undergo the seismic retrofits and renovations using the advanced fibre composite systems in order to effectively meet the SPC-2 guidelines required per state law. The level of details and complexities addressed in this hospital showcase the application diversity of both the analysis method and the composite systems installed.

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