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Enhanced Seismic Retrofitting and Performance Assessment for Cripple Walls Using Modern Materials and Computational Methods

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Abstract

This study presents an advanced investigation into the seismic performance and retrofitting strategies for cripple walls, focusing on the integration of modern materials and computational techniques. Cripple walls, common in pre-1960 residential buildings, are highly vulnerable to seismic forces, often leading to soft-story collapses. This research builds on earlier experimental studies by incorporating state-of-the-art materials such as fiber-reinforced composites and advanced retrofitting solutions. The study also utilizes computational simulations, including finite element modeling and machine learning-based predictive tools, to evaluate the dynamic behavior and failure mechanisms under varied loading scenarios, including ordinary and near-fault ground motions. The experimental program is expanded to explore the impact of material enhancements, structural configurations, and environmental factors on lateral strength, deformation limits, and seismic toughness. Results demonstrate significant improvements in lateral stiffness and strength when using modern retrofitting techniques compared to conventional methods. Computational models validate experimental findings, offering insights into optimizing retrofit designs for varying building typologies and seismic intensities. The findings contribute to the development of performance-based design guidelines, emphasizing resilience and cost-effectiveness. This research bridges the gap between experimental studies and advanced computational approaches, offering a comprehensive framework for enhancing the seismic safety of cripple walls in existing and new constructions.

Keywords: *Mappings, convergence, hyperbolic spaces, iteration process.*

1. Introduction

The seismic performance of residential buildings is a critical area of structural engineering, especially in earthquake-prone regions. Cripple walls—short wood-framed walls located between the foundation and the first floor—are a distinctive feature of older residential constructions, particularly pre-1960 homes. These walls, while designed to provide structural support and accommodate uneven terrains, have demonstrated significant vulnerability to seismic forces in historical earthquakes. Events such as the 1983 Coalinga, 1989 Loma Prieta, and 1994 Northridge earthquakes revealed the susceptibility of cripple walls to catastrophic failure modes, including soft-story collapses. These collapses often lead to severe structural damage, economic losses, and risks to human safety, highlighting the urgent need to improve their seismic resilience [1].

The vulnerability of cripple walls arises from several construction-related factors [2]. Many cripple walls are minimally braced or unbraced, leaving them without sufficient lateral resistance to seismic forces. Common deficiencies include poor anchoring to foundations, material degradation over time, and inadequate lateral bracing. These shortcomings are exacerbated by environmental conditions such as high moisture levels in crawl spaces, which accelerate the deterioration of wood and connectors. The combination of these factors significantly increases the risk of failure during seismic events, making the enhancement of cripple wall performance a priority in retrofitting efforts and modern design practices.

Traditional retrofitting approaches, such as adding structural panels and improving anchorage, have shown some success in enhancing cripple wall performance [3]. However, these methods often rely on empirical design values extrapolated from tests on full-height shear walls, which may not fully capture the unique dynamics of cripple walls. The height-to-length ratio and localized load transfer characteristics of cripple walls introduce complexities that empirical approaches cannot adequately address. Furthermore, stepped cripple walls, commonly found in hillside constructions, present additional challenges due to their asymmetric configurations and complex load paths. Addressing these issues requires an integrated approach that combines experimental investigation with advanced analytical and computational tools.

The emergence of modern materials and computational methodologies offers transformative potential for understanding and improving the performance of cripple walls [4]. Advanced materials such as fiber-reinforced polymers (FRPs), engineered wood products, and composites provide superior strength, durability, and moisture resistance compared to traditional materials. Meanwhile, computational techniques, including finite element analysis (FEA), machine learning algorithms, and multi-physics simulations, enable detailed evaluations of cripple wall behavior under complex loading conditions. These *tools complement experimental findings, facilitating optimization of retrofitting designs and uncovering insights that would be challenging to obtain through physical testing alone.*

The experimental component of this study explores critical variables such as wall height, slope, bracing percentage, gravity loads, and finishing materials like stucco [5]. Both level and stepped cripple walls are subjected to conventional and modern retrofitting techniques to evaluate their seismic performance. Stepped walls, which pose unique challenges due to their slopes and framing configurations, are analyzed in detail to assess the impact of geometric and structural variations. Complementary computational simulations provide a deeper understanding of failure mechanisms, load transfer pathways, and material performance, bridging the gap between experimental data and practical applications.

Beyond technical insights, this research also seeks to inform updates to building codes and seismic retrofitting guidelines. Current standards often rely on simplified assumptions that fail to capture the intricate behavior of cripple walls under seismic loads. By providing a comprehensive evaluation of material and design innovations, this study aims to influence policy changes that promote safer and more resilient construction practices [6].

The implications of this study extend beyond academic research, addressing the broader societal challenges associated with seismic risk. With millions of residential buildings incorporating cripple walls, particularly in seismically active regions, improving their resilience has direct implications for public safety and economic stability. By bridging traditional empirical methods with advanced analytical approaches, this research provides a robust framework for addressing the unique challenges of cripple wall retrofitting. The findings underscore the importance of integrating cutting-edge materials and computational tools to enhance the seismic performance of these critical structural elements.

Future studies should expand on the integration of smart materials, such as self-sensing composites, and explore the potential of machine learning to refine predictive models [7]. Real-time monitoring systems embedded in retrofitted cripple walls could provide valuable data on their performance during seismic events, enabling continuous improvements to retrofitting strategies. Additionally, collaborative efforts between researchers, engineers, and policymakers are essential to ensure that the benefits of these advancements are widely accessible, particularly for low-income communities that often face the greatest risks from seismic events.

In conclusion, this study represents a significant step toward enhancing the seismic resilience of cripple walls through the integration of innovative materials and computational technique [8]s. By addressing existing gaps and exploring new frontiers, it lays the groundwork for safer, more resilient residential buildings capable of withstanding the challenges posed by future earthquakes.

2. Materials and Methods

The effectiveness of cripple walls in resisting seismic forces is closely tied to the properties of the materials used, construction details, and retrofitting techniques. This section outlines the materials employed, the experimental framework, and the computational approaches used to evaluate and improve the seismic performance of cripple walls. By combining advanced materials with cutting-edge simulation tools, this research aims to bridge the gap between traditional retrofitting practices and modern engineering methodologies.

2.1 Materials

Materials utilized in this study included both traditional construction materials and modern retrofitting solutions. Cripple walls in older buildings were primarily constructed using Douglas fir or other softwoods prone to degradation over time. To maintain consistency with historical construction practices, Douglas fir was selected as the base material for the experimental specimens. For sill plates, pressure-treated Hem Fir was used due to its resistance to moisture-induced deterioration, a common issue in crawl spaces under residential structures. Stucco was incorporated into selected specimens to assess its lateral resistance contribution, applied in two layers—a scratch coat and a brown coat-while omitting the final color coat to ensure uniformity with prior studies.

Modern retrofitting materials were also evaluated to enhance the seismic resilience of cripple walls. Fiber-reinforced polymers (FRPs), known for their lightweight, high durability, and ease of installation, were used to provide lateral stiffness and strength. Both carbon and glass FRPs were tested to compare performance. Engineered wood products, such as 15/32-inch thick oriented strand board (OSB) panels, were employed as bracing elements for both level and stepped cripple wall configurations, offering improved dimensional stability and resistance to splitting. Additionally, hybrid systems combining structural plywood and FRPs were tested to explore potential synergistic effects in improving lateral performance.

2.2 Experimental Framework

The experimental framework involved constructing 30 cripple wall specimens, including both level and stepped wall configurations. Key variables included wall height and slope, bracing percentage, and the presence of finish materials. Specimens were built with wall heights of 2 feet (0.61 m) and 4 feet (1.22 m) for level walls, while stepped walls featured slopes of 1-in-3 and 1-in-2 to simulate typical hillside construction. Bracing levels varied between fully braced (100%) and partially braced (66%) using OSB panels. Some specimens included stucco finishes to assess the interaction of finishes with the primary bracing system.

The specimens underwent quasi-static reversed cyclic loading to simulate seismic ground motions, with two distinct protocols representing ordinary ground motions (10% probability of exceedance in 50 years) and near-fault ground motions (2% probability of exceedance in 50 years). Gravity loads of 450 lbs/ft (6.57 kN/m) and 100 lbs/ft (1.46 kN/m) were applied to replicate single- and two-story residential structures. Horizontal actuators imposed lateral displacements, while vertical compression was maintained using a tie-down system. Instrumentation, including load cells, displacement transducers, and strain gauges, captured precise measurements of lateral forces, displacements, and material deformations.

2.3 Computational Modeling

To complement the experimental findings, computational modeling was performed using finite element analysis (FEA). The models accounted for material nonlinearity, such as nail withdrawal, wood crushing, and FRP delamination, as well as contact mechanics and dynamic loading conditions based on real-world seismic records. Additionally, a machine learning framework was implemented to predict failure patterns and optimize retrofitting designs. Supervised learning algorithms were trained on experimental data using input features such as material properties, wall geometry, and loading conditions to identify critical parameters influencing lateral strength and deformation limits.

2.4 Data Analysis and Validation

Data analysis and validation were conducted to compare experimental results with computational models. Key performance metrics included lateral strength and stiffness at peak loads and maximum displacements, drift ratios to determine deformation limits, and identified failure mechanisms to evaluate the efficacy of retrofitting techniques. Statistical analyses quantified the impact of variables, and sensitivity analyses highlighted the most influential parameters for design optimization.

This study introduces several innovative methodologies, including the use of hybrid retrofitting materials combining FRPs and OSB for enhanced seismic resilience, the integration of machine learning for predictive modeling and performance-based design, and the application of multi-physics FEA to capture complex interactions within cripple wall systems under seismic loading. These advancements provide a robust framework for evaluating and improving the seismic performance of cripple walls, contributing to the development of safer and more resilient residential structures. The insights gained from this research form the foundation for the results and discussion presented in subsequent sections.

3. Result

The study provides critical insights into the seismic performance of cripple walls, focusing on material behavior, retrofitting effectiveness, and deformation under dynamic loading. Through comprehensive experimental and computational analysis, key parameters influencing lateral strength, stiffness, and deformation limits are identified, offering practical guidance for improving the resilience of older residential buildings.

The results indicate that lateral strength and stiffness are directly influenced by material selection and retrofitting techniques. Fully braced cripple walls exhibited superior seismic resistance compared to partially braced counterparts, demonstrating the importance of comprehensive structural coverage. The addition of stucco finishes enhanced stiffness modestly, serving as an auxiliary reinforcement.

Stepped cripple walls displayed slightly higher lateral strength than level walls due to their stepped configuration, which inherently provides increased stability. However, stepped walls also revealed greater torsional vulnerabilities under asymmetric loading, necessitating targeted retrofitting strategies to mitigate these risks.

The study highlights the comparative performance of traditional and modern retrofitting materials. Douglas fir was used for its consistency with historical practices, while modern materials such as fiber-reinforced polymers (FRPs) and hybrid systems demonstrated marked improvements. FRPs, particularly carbon-based, significantly enhanced stiffness and deformation tolerance due to their lightweight, high-tensile properties. Hybrid systems, combining OSB panels with FRPs, outperformed individual materials, emphasizing their synergistic benefits in seismic applications.

Deformation behavior was evaluated using drift ratios as a key performance metric. Fully braced level walls exhibited higher drift capacity than partially braced specimens, with shorter walls (2 feet) showing better deformation control compared to taller walls (4 feet). Taller walls experienced greater uplift forces and moments, reducing their drift limits.

Stepped walls achieved comparable drift ratios to level walls but experienced localized damage at step interfaces. The "discontinuous" stud framing mitigated damage by accommodating rotational movements, whereas "continuous" stud framing led to stud bending and splitting under lateral forces.

The applied loading protocols—ordinary and near-fault seismic motions—produced distinct responses. Near-fault loading, characterized by high-intensity and rapid reversals, resulted in greater deformation and accelerated strength degradation compared to ordinary loading protocols. These findings underline the necessity of considering site-specific seismic hazards in retrofitting designs.

Finite element analysis (FEA) validated experimental observations by accurately simulating critical failure mechanisms, such as nail withdrawal, wood crushing, and FRP delamination. The simulations aligned closely with physical test results, offering detailed insights into stress concentrations and material interactions. These findings provide actionable data for refining retrofitting designs.

The integration of machine learning enhanced predictive modeling, identifying material properties, wall geometry, and bracing percentage as the most significant predictors of seismic performance. This approach enables optimization of retrofitting strategies to achieve improved outcomes.

Stucco finishes contributed moderately to lateral strength and stiffness. While not as impactful as structural bracing, the two-layer application of scratch and brown coats provided additional resistance against lateral forces. The exclusion of the color coat ensured alignment with existing studies and isolated the structural effects of the finishes.

Statistical analysis confirmed the significance of bracing percentages and retrofitting materials as primary factors influencing seismic performance. Sensitivity analysis highlighted the potential benefits of moisture-resistant treatments, particularly for structures exposed to high humidity in crawl spaces, which would reduce material degradation and improve long-term performance.

This study introduced several innovations in cripple wall evaluation:

1. *Hybrid Systems: Combining FRPs and OSB panels demonstrated enhanced seismic resilience through material synergy.*
2. *Computational Modeling: Multi-physics FEA models provided a detailed understanding of complex material behaviors under seismic loading.*
3. *Predictive Modeling: Machine learning algorithms offered data-driven optimization, enabling the identification of critical performance parameters.*
4. *These advancements not only improve the understanding of cripple wall behavior but also establish a robust framework for designing and implementing effective seismic retrofitting solutions.*

4. Discussion

The results of this study provide critical insights into the seismic performance of cripple walls, shedding light on the efficacy of modern retrofitting techniques and advanced materials. However, the complex behavior of cripple walls under seismic loads and environmental conditions calls for further investigation. This discussion situates the findings within the broader context of structural engineering research and outlines future directions for advancing the field [9].

Modern retrofitting materials, such as fiber-reinforced polymers (FRPs) and oriented strand board (OSB) panels, have demonstrated their effectiveness in enhancing the lateral strength and stiffness of cripple walls. However, the exploration of emerging materials, such as bio-composites, self-healing polymers, and nanotechnology-enhanced FRPs, could yield significant advancements. For instance, integrating nanoparticles into FRPs may enhance their resistance to fatigue, delamination, and long-term degradation.

The promising performance of hybrid systems, which combine OSB panels with FRPs, highlights the need for further research into optimizing material combinations [10]. Future studies should investigate the structural behavior of other hybrid configurations, such as those incorporating structural adhesives or high-performance laminates, to maximize lateral resistance and deformation capacity.

This study confirms that full bracing provides superior seismic performance; however, practical constraints often necessitate partial retrofitting [11]. Advanced research could focus on optimizing partial bracing configurations to achieve comparable performance with reduced material use. Parametric analyses using computational tools, such as finite element analysis (FEA), can aid in identifying effective partial bracing strategies that balance cost-efficiency with structural integrity.

Furthermore, tailored retrofitting solutions that account for specific structural configurations, such as taller walls or stepped cripple walls, are essential. Modular retrofitting kits with pre-engineered components designed for various wall geometries and sizes could streamline implementation while maintaining safety standards.

While the study tested cripple walls under ordinary and near-fault seismic protocols, real-world earthquakes often involve complex, multi-directional ground motions. Future research should explore advanced loading scenarios that simulate realistic seismic events, including variable frequencies, durations, and directions. Multi-physics simulations could offer a comprehensive understanding of how cripple walls and retrofitting systems behave under such conditions.

Additionally, many buildings are subjected to multiple earthquakes during their lifespan. Investigating the cumulative effects of repeated seismic loading on retrofitted cripple walls could provide valuable insights into long-term performance and inform maintenance strategies [12].

The integration of machine learning (ML) into this study highlights its potential for predictive modeling and optimization of retrofitting designs [13]. Expanding ML applications to include larger datasets with diverse materials, geometries, and seismic conditions could enhance predictive accuracy. Advanced techniques such as deep learning and reinforcement learning could uncover hidden relationships between design variables and seismic performance.

Real-time decision-making tools powered by ML could further revolutionize retrofitting practices. For example, mobile applications leveraging trained ML models could offer on-site recommendations for retrofitting strategies based on building-specific data, making advanced techniques more accessible to practitioners [14].

Environmental factors, particularly moisture exposure in crawl spaces, significantly impact the performance of cripple walls. Advanced studies should focus on developing moisture-resistant materials and coatings, such as hydrophobic treatments or anti-microbial additives, to prevent rot and material degradation.

The interaction between environmental conditions and seismic performance also warrants investigation. Moisture-compromised materials may exhibit altered mechanical properties under seismic loads, potentially undermining retrofitting effectiveness. Experimental studies replicating combined environmental and seismic stresses could provide a more nuanced understanding of these interactions [15].

Stepped cripple walls in hillside constructions pose unique challenges due to their geometric configurations. This study demonstrated the advantages of "discontinuous" stud framing at step interfaces, which allowed rotational flexibility and reduced damage. However, alternative solutions, such as base isolation systems or flexible connectors, could be explored to further enhance performance.

Advanced computational models, particularly three-dimensional FEA, are critical for understanding the torsional and lateral dynamics of stepped walls. These models could help design retrofitting systems that address the specific vulnerabilities of these configurations, ensuring greater resilience.

Smart materials and technologies present exciting opportunities for the future of cripple wall retrofitting [16]. Self-sensing materials capable of monitoring stress and strain in real time could provide early warnings of structural vulnerabilities, enabling proactive maintenance. Additionally, adaptive systems, such as smart dampers or actuators, could dynamically adjust stiffness and damping properties during seismic events to optimize energy dissipation.

Research into the feasibility, cost, and implementation of such technologies could pave the way for their integration into retrofitting practices, significantly enhancing building safety.

The lack of specific design standards for cripple walls remains a critical gap in the field. Current guidelines often extrapolate data from full-height shear walls, which may not accurately represent cripple wall behavior [17]. Advanced studies should aim to establish dedicated design codes that reflect the unique characteristics of cripple walls and their retrofitting requirements.

Performance-based design approaches should also be prioritized, enabling engineers to tailor retrofitting solutions to achieve specific resilience objectives. For instance, designs could focus on optimizing seismic safety while minimizing retrofitting costs, providing greater flexibility and encouraging innovative solutions [18].

Cripple walls are prevalent in older residential buildings, many of which are located in low-income communities. Ensuring that retrofitting solutions are cost-effective and widely accessible is essential for reducing seismic risk on a broad scale [19]. Future research should explore strategies for balancing performance with affordability, such as developing low-cost retrofitting materials or leveraging economies of scale in production.

Policy interventions, such as government subsidies or tax incentives, could further promote the adoption of retrofitting measures. Research into the economic impact of retrofitting programs could provide valuable evidence to support these initiatives, encouraging widespread implementation [20].

5. Future Direction

The future of cripple wall research lies in integrating experimental rigor with computational innovation. Hybrid methodologies that combine advanced material testing, multi-physics simulations, and data-driven approaches are essential for addressing the complex challenges of seismic retrofitting. Collaboration among academia, industry, and policymakers can accelerate the development of next-generation retrofitting techniques.

Expanding research to include global contexts could also provide valuable insights. While cripple walls are common in certain regions, studying their performance under diverse seismic and environmental conditions would enhance the generalizability of findings. International partnerships and knowledge-sharing initiatives could play a key role in advancing the field.

6. Conclusion

This study has provided critical insights into the seismic performance of cripple walls, highlighting the importance of modern retrofitting materials, optimized configurations, and advanced computational techniques. The findings underscore the significant benefits of using materials such as fiber-reinforced polymers (FRPs), hybrid retrofitting systems, and tailored configurations for both level and stepped cripple walls. Full bracing coverage, innovative "discontinuous" stud framing, and the integration of machine learning tools have emerged as key strategies for enhancing lateral strength, stiffness, and deformation limits.

However, this study also emphasizes the need for further research to address the complexities of seismic behavior under realistic loading scenarios, the long-term performance of retrofitting systems, and the impact of environmental conditions on cripple wall resilience. Future advancements should focus on the development of next-generation materials, such as self-healing composites and smart systems, which can dynamically adapt to seismic forces and provide real-time monitoring.

The findings also underscore the importance of accessibility and affordability in retrofitting practices, especially for low-income communities with older residential buildings. Policymakers, engineers, and researchers must collaborate to develop cost-effective solutions and establish dedicated guidelines for cripple wall retrofitting, ensuring equitable access to seismic safety measures.

In conclusion, advancing the science of cripple wall retrofitting will require a multidisciplinary approach that combines experimental rigor, computational innovation, and practical implementation. By addressing these challenges, we can enhance the seismic resilience of vulnerable structures, safeguard communities, and contribute to the broader goals of sustainable and disaster-resistant infrastructure.

References

[1] *Freddi, F., Galasso, C., Cremen, G., Dall'Asta, A., Di Sarno, L., Giaralis, A., ... & Woo, G. (2021). Innovations in earthquake risk reduction for resilience: Recent advances and challenges.* International Journal of Disaster Risk Reduction, 60, *102267.*

[2] *Schuldt, S. J., Nicholson, M. R., Adams, Y. A., & Delorit, J. D. (2021). Weather-related construction delays in a changing climate: a systematic state-of-the-art review.* Sustainability, 13*(5), 2861.*

[3] *Lennick, D., & Kiel, F. (2011). Moral intelligence 2.0: Enhancing business performance and leadership success in turbulent times. Pearson Prentice Hall.*

[4] *Ciesielski, P. N., Pecha, M. B., Bharadwaj, V. S., Mukarakate, C., Leong, G. J., Kappes, B., ... & Nimlos, M. R. (2018). Advancing catalytic fast pyrolysis through integrated multiscale modeling and experimentation: Challenges, progress, and perspectives. Wiley Interdisciplinary Reviews:* Energy and Environment, 7*(4), e297.*

[5] *Angulo-Ibáñez, Q., Mas-Tomás, Á., Galvañ-LLopis, V., & Sántolaria-Montesinos, J. L. (2012). Traditional braces of earth constructions.* Construction and Building Materials, 30, *389-399.*

[6] *Akadiri, O. P. (2011). Development of a multi-criteria approach for the selection of sustainable materials for building projects.*

[7] *Shojaei, A., & Khasraghi, S. S. (2021). Self-healing and self-sensing smart polymer composites. In Composite Materials (pp. 307-357). Elsevier.*

[8] *Zsarnóczay, A., & Deierlein, G. G. (2020, September). PELICUN–A computational framework for estimating damage, loss and community resilience. In Proceedings, 17th World Conference on Earthquake Engineering,(Sendai: WCEE).*

[9] *Johri, A., & Olds, B. M. (2011). Situated engineering learning: Bridging engineering education research and the learning sciences.* Journal of Engineering Education, 100*(1), 151-185.*

[10] *Amran, Y. M., El-Zeadani, M., Lee, Y. H., Lee, Y. Y., Murali, G., & Feduik, R. (2020, October). Design innovation, efficiency and applications of structural insulated panels: A review. In Structures (Vol. 27, pp. 1358-1379). Elsevier.*

[11] *Cao, X. Y., Shen, D., Feng, D. C., Wang, C. L., Qu, Z., & Wu, G. (2022). Seismic retrofitting of existing frame buildings through externally attached sub-structures: State of the art review and future perspectives.* Journal of Building Engineering, 57, *104904.*

[12] *Schiller, B. (2021). Seismic Performance of Existing and Retrofitted Cripple Walls. University of California, San Diego.*

[13] *Deb, C., Dai, Z., & Schlueter, A. (2021). A machine learning-based framework for cost-optimal building retrofit.* Applied Energy, 294, *116990.*

[14] *Goodchild, M. F. (2000). Part 1 Spatial analysts and GIS practitioners: The current status of GIS and spatial analysis.* Journal of Geographical Systems, 2*(1), 5-10.*

[15] *Li, S., Li, C., & Wang, F. (2024). Computational experiments of metal corrosion studies: a review.* Materials Today Chemistry, 37, *101986.*

[16] *Ibn-Mohammed, T., Mustapha, K. B., Godsell, J., Adamu, Z., Babatunde, K. A., Akintade, D. D., ... & Koh, S. C. L. (2021). A critical analysis of the impacts of COVID-19 on the global economy and ecosystems and opportunities for circular economy strategies. Resources,* Conservation and Recycling, 164, *105169.*

[17] *Schiller, B. (2021). Seismic Performance of Existing and Retrofitted Cripple Walls. University of California, San Diego.*
[18] *Sberna, A. P. (2024). Engineered design frameworks for the seismic retrofitting of existing structures.*
[19] *Egbelakin, T., Wilkinson, S., & Ingham, J. (2014). Economic impediments to successful seismic retrofitting decisions.* Structural Survey, 32*(5), 449-466.*
[20] *Leadbeater, B. J., & Gladstone, E. J. (2016). Supporting schools for the widespread implementation of evidence-based mental health promotion programs: What is needed?. In Mental Health and Wellbeing through Schools (pp. 27-38). Routledge.*